WRM: Weather Routing Metaheuristic

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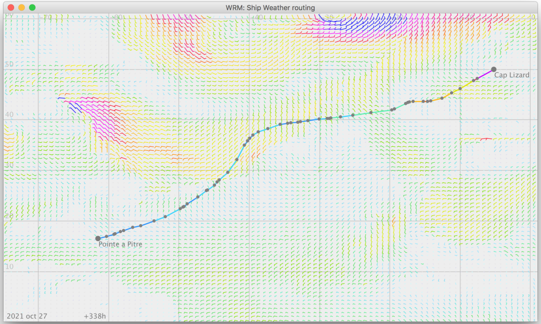
Ship weather routing



Search optimised routes for ships in an environment that changes with the time.

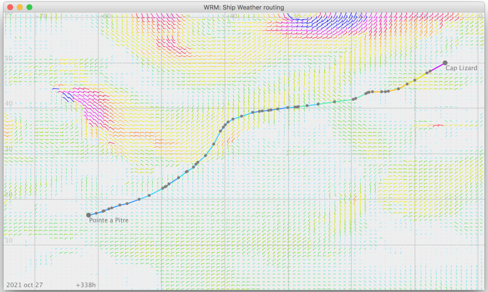
Plan

Ship weather routing

WRM : a new approach for ship weather routing

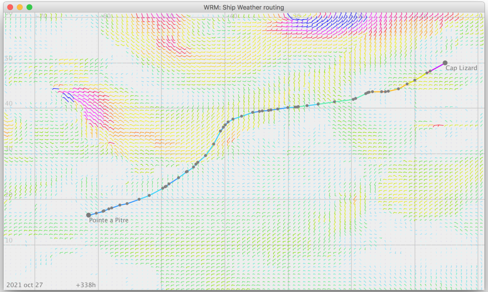
WRM running

Ship weather routing



Search optimised routes for ships in an environment that changes with the time.

Ship weather routing

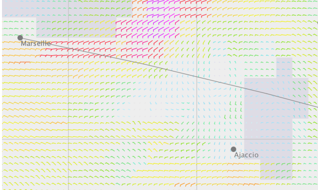


Plan

- the problem,
- WRM approach,
- experimentations.

Search optimised routes for ships in an environment that changes with the time.

Ship weather routing

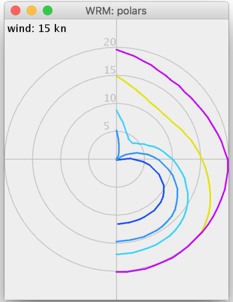


Environmental factors

- wind (speed, direction),
- waves (direction, height,. . .),

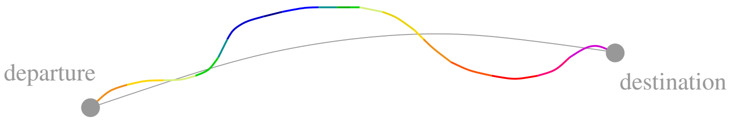
affect ship performances

- *consumption*,
- *progression*,



SOG with 15-knots wind, power levels 5 kW, 10 kW, 15 kW, 25 kW, 50 kW

Ship weather routing : Route



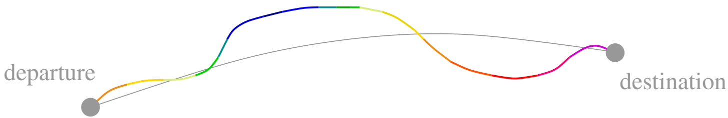
Route :

- a trajectory,
- a value representing the *speed* at each point of the trajectory.

speed parameter

- SOG, **engine power level**, shaft rotation speed,. . .

Ship weather routing



Optimize :

- cost,
- safety, green gazes emissions, comfort, duration,. . .

Constraints : dates, forbidden/penalized regions, bad weather conditions,. . .

The search space is continuous in space as in time

Ship weather routing

Publications :

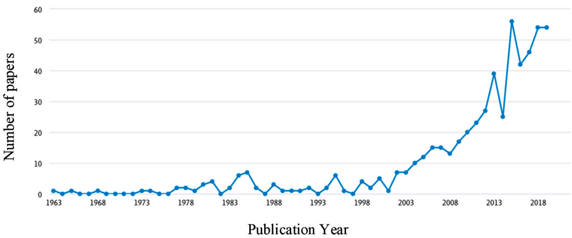


Fig. 2. Publishing trend in the area of ship weather routing and voyage optimization.
Source: Scopus February 2020.

Zis, T.P., Psaraftis, H.N., Ding, L. : Ship weather routing : A taxonomy and survey. Ocean Engineering 213, 107697 (2020).

Ship weather routing

Existing approaches :

- **isochrones, isopones :** time/fuel consumption,
- **dynamic programming :** 2D, 3D,
- **Dijkstra based algorithms,**
- **genetic algorithms,**
- ...

Ship weather routing

Existing approaches :

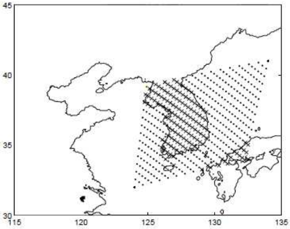
- **isochrones, isopones :** time/fuel consumption,
- **dynamic programming :** 2D, 3D,
- **Dijkstra based algorithms,**
- **genetic algorithms,**
- ...

WRM : metaheuristic

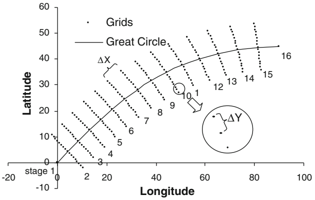
- launch many times a simple forward algorithm on *simplified versions of the problem*

Grandcolas, S., A metaheuristic algorithm for ship weather routing,
to appear in *Operations Research Forum*, 2022.
DOI : 10.1007/s43069-022-00140-0

Existing approaches



“Multi-Objective Optimization of Motor Vessel Route.”
Marie, S., Courteille, E. 2009



“Development of a novel forward dynamic programming method for weather routing’”
Shao, W., Zhou, P., Thong, S. 2011

Existing approaches

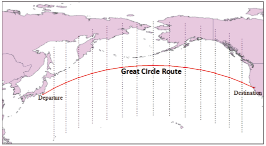
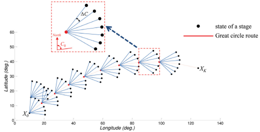
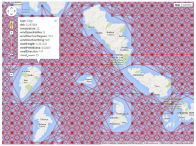


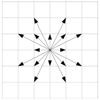
Fig. 1. Grid system and Great Circle Route



"An Ant Colony Algorithm for efficient ship routing."
Tsou, M.C., Cheng, H.C. 2013

"The optimization of ship weather-routing algorithm based on the composite influence of multi-dynamic elements."
Fang, M.C., Lin, Y.H. 2015





"Minimizing the fuel consumption and the risk in maritime transportation : A bi-objective weather routing approach"
Veneti, A., Makrygiorgos, A., Konstantopoulos, C., Pantziou, G., Vetsikas, I. 2017

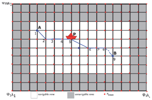


Fig. 1 The grid as navigational chart

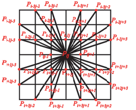
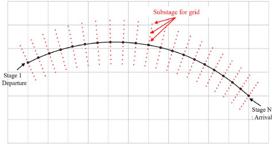
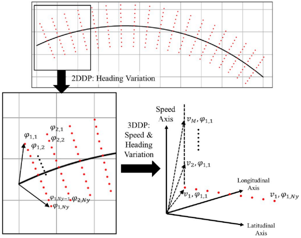


Fig. 2 Illustration of all vessel movement possibilities in a grid

"Multi-Objective Weather Routing of Sailing Vessels."
Życzkowski, Marcin and Rafal Szlapczynski. 2017

Existing approaches : 3D dynamic programming





Kim, K.I., Lee, K.M. : Dynamic Programming-Based Vessel Speed Adjustment for Energy Saving and Emission Reduction. Energies 11(5) (2018).

Existing approaches : Dijkstra's algorithm

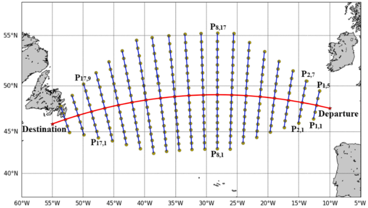


Fig. 2. Waypoints between departure and destination.

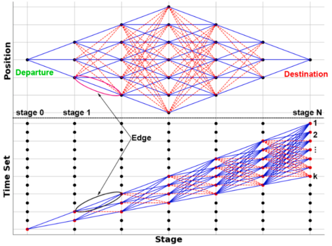


Fig. 3. An illustration of the 3D graph (a grid of waypoints) system for voyage optimization.

Wang, H., Mao, W., Eriksson, L. : A Three-Dimensional Dijkstra's algorithm for multi- objective ship voyage optimization. Ocean Engineering 186, 106131 (2019).

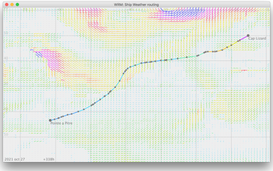
WRM : Weather Routing Metaheuristic

Ship weather routing

WRM : a new approach for ship weather routing

WRM running

WRM



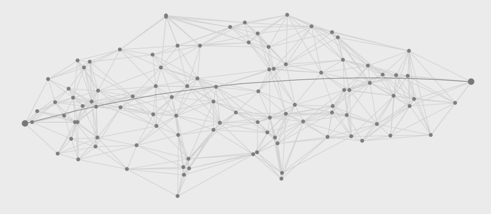
Problem :

- *departure*, *destination*,
- a time window,
- a weather forecast,
- *speed parameter* : engine power level

Goal : find a route whose total cost is minimal

The idea : solve a series of **simplified versions of the problem** gradually focusing on the most promising area.

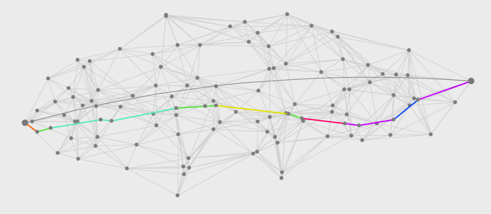
WRM : simplified version of the problem



$P = \{p_0, p_1, \ldots, p_n\}$	*points*
$L = \{(p_i, p_j),\ p_i, p_j \in P\}$	*legs*
$W = \{l_1, l_2, \ldots, l_m\}$	*power level values*
$[t_{min}, t_{max}]$	*time window*
$\mathcal{F}$	*weather forecast*

(P, L) : directed, acyclic.

WRM : simplified version of the problem



$P = \{p_0, p_1, \ldots, p_n\}$	*points*
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$W = \{l_1, l_2, \ldots, l_m\}$	*power levels*
$[t_{min}, t_{max}]$	*time window*
$\mathcal{F}$	*weather forecast*

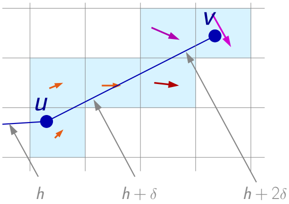
Route : $\langle t_{dep},\ (u_0, u_1, \ldots, u_k),\ (w_0, w_1, \ldots, w_{k-1})\rangle$

for each i, $(u_i, u_{i+1}) \in L$ and $w_i \in W$, constant power level on each leg.

WRM : simplified version of the problem

Evaluation of crossings :

- $duration(u, v, w, t, \mathcal{F})$
- $cost(u, v, w, t, \mathcal{F})$



duration and cost to cross from u to v at the date t at engine power level w, given the forecast $\mathcal{F}$.

WRM : simplified version of the problem

Evaluation of crossings :

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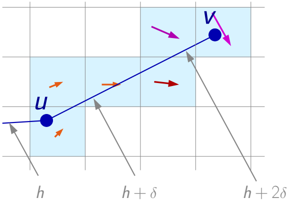
- $cost(u, v, w, t, \mathcal{F})$



$$P = P_{idle} + (P_{calm} + P_{wind}) \times C_{waves}$$

WRM : simplified version of the problem

Evaluation of crossings :

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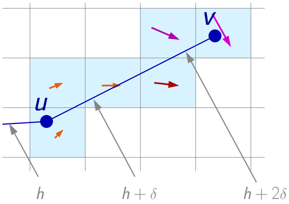
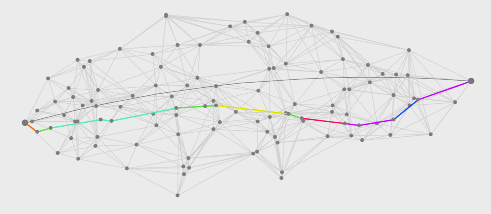


$$P = P_{idle} + (P_{calm} + P_{wind}) \times C_{waves}$$

$$P_{calm} = c_1 \times v^{2.5}$$
$$P_{wind} = c_2 \times A \times s_a^2 \times \cos\theta_a$$
$$C_{waves} = f(\lambda, L, \theta_w, v)$$

v : SOG
A : projected surface area
θ_a : apparent wind to ship angle
s_a : apparent wind speed
λ : waves length
L : ship length
θ_w : waves to ship angle

WRM : simplified version of the problem



Valid route : $\langle t_{dep},\ (u_0, u_1, \ldots, u_k),\ (w_0, w_1, \ldots, w_{k-1})\rangle$

satisfies

$$t_{dep} \geq t_{min} \quad and \quad t_{arr} \leq t_{max}$$

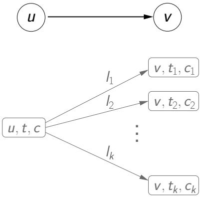
where t_{arr} is the arrival date

WRM : searching a good route

Dated costs : (u, t, c)

there is a route that reaches u at date t whose cost is c

Propagation :



Combinatorial explosion : discard the dated costs that seem the least promising.

Best route : *Arrival* best dated cost.

WRM : simplified version of the problem

Improvements :

- minimal arrival dates (forward exploration),
- maximal arrival dates (backward exploration),
- **minimal bounds** of the costs,

Number of legs evaluations :

$$\mathcal{O}(|L| \times |W| \times K)$$

K : given limit of the number of dated costs for each vertex

WRM : Metaheuristic algorithm

algorithm WRM $(dep, dest, t_{min}, t_{max}, P_{min}, P_{max}, \mathcal{F}, nb_{runs})$

$\pi :=$ initial parameters,
repeat nb_{runs} **times**
π-generate a simplified problem $\mathcal{P}$,
solve $\mathcal{P}$ propagating dated costs,
update *bestRoute*,
update π,
end loop
return *bestRoute*,

- *first runs* : unconstrained generation,
- *following runs* : strengthen π parameters step by step, so as to converge towards the most promising areas

Metaheuristic : graphs generation

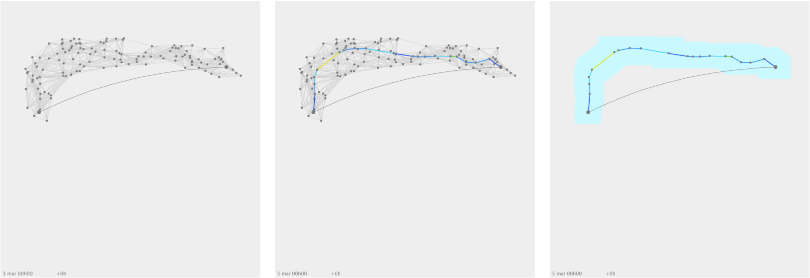
Generate problem

Metaheuristic : graphs generation

Search a good route

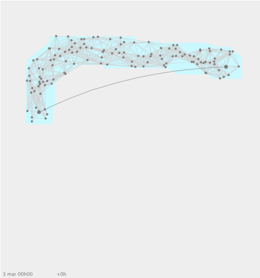
Metaheuristic : graphs generation

Mark surrounding area



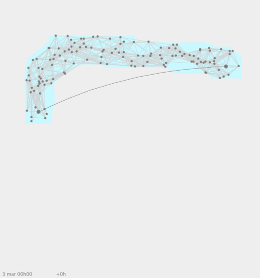
Metaheuristic : graphs generation

Generate problem



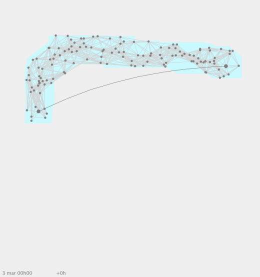
Metaheuristic : graphs generation

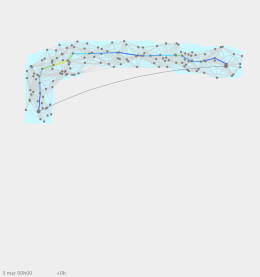
Search a route



Metaheuristic : graphs generation

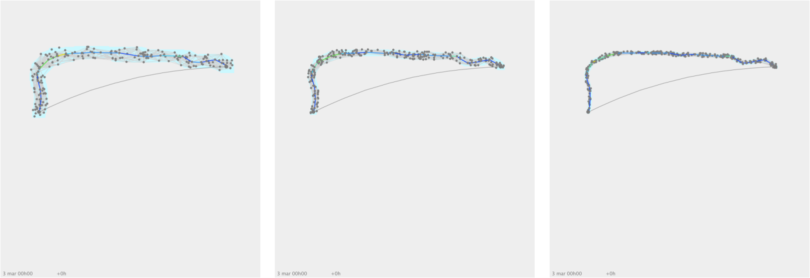
Mark surrounding area





Metaheuristic : graphs generation

Strengthen generation parameters



- perimeter,
- time windows,
- steps and ranges of the power levels.

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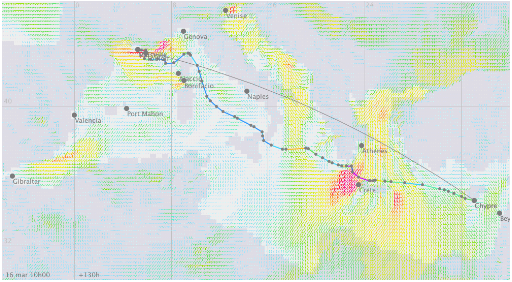
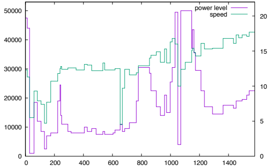
Ship weather routing

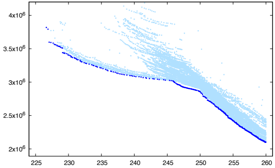
WRM : a new approach for ship weather routing

WRM running

WRM : Marseille-Chypre [130h, 260h]



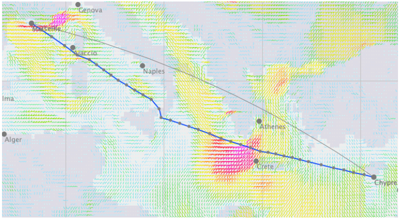


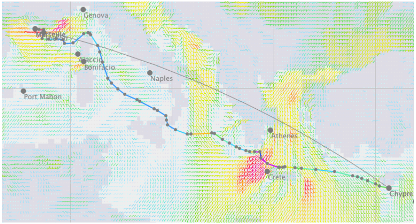


l=1581.5NM/1394.1NM sp=12.2kn cost=2101399.2 130.0h-260.0h (130.0h) (16 mar 10h00 to 21 mar 19h57) 57 points 141.6s

Forecast : NOAA (National Oceanic and Atmospheric Administration), GFS atmospheric and waves models, 384h, 3 hours intervals, resolution 0.25°.

WRM : Marseille-Chypre [130h, 260h], shortest route





Direct route (simulation) :

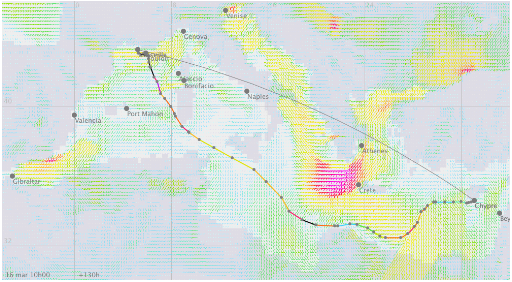
- 1451.2 nautic miles,
- 128.5 hours,
- cost 4315241 (constant power 31.5kw)

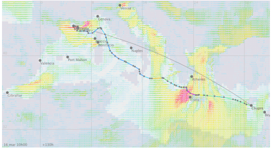
Route returned by WRM :

- 1581.5 nautic miles,
- 130.0 hours (avg speed 12.2 knots),
- cost 2101399

cost at idle : 677237

WRM : Marseille-Chypre penalize bad weather conditions



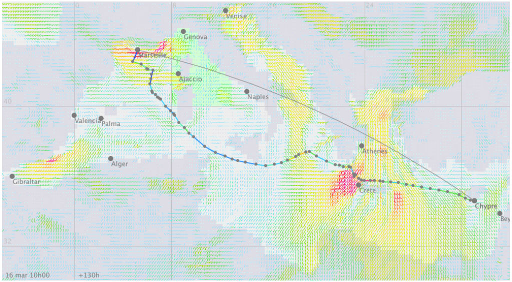


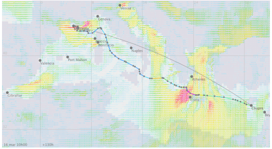
wind speed	$\geq$ 22 knots
wind heading	$\leq 120^\circ$
waves height	$\geq$ 1.5 m
waves heading	$\geq 10^\circ$

l=1703.9NM/1394.1NM sp=16.3kn cost=3704002.4 155.5h-260.0h (104.5h) (17 mar 11h27 to 21 mar 19h59) 50 points 309.8s

l=1581.5NM/1394.1NM sp=12.2kn cost=2101399.2 130.0h-260.0h (130.0h) (16 mar 10h00 to 21 mar 19h57) 57 points 141.6s

WRM : Marseille-Chypre ECA [130h, 260h]



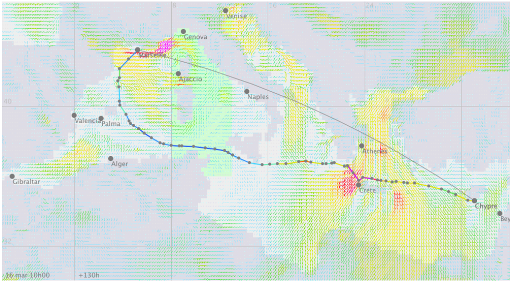


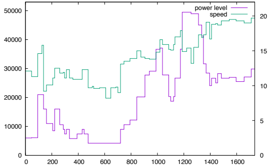
ECA (Emission Control Areas) : cost increase 20%

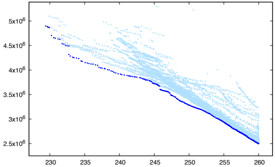
l=1631.4NM/1394.1NM sp=12.8kn cost=2191371.0 132.5h-260.0h (127.5h) (16 mar 12h27 to 21 mar 19h59) 57 points 103.2s

l=1581.5NM/1394.1NM sp=12.2kn cost=2101399.2 130.0h-260.0h (130.0h) (16 mar 10h00 to 21 mar 19h57) 57 points 141.6s

WRM : Marseille-Chypre ECA [130h, 260h]







l=1737.9NM/1394.1NM sp=13.4kn cost=2501611.2 130.0h-260.0h (130.0h) (16 mar 10h00 to 21 mar 20h01) 59 points 54.4s

Merci !