Arab Academy

for Science , Technology and Maritime Transport

13 Marlog 2024

The International Maritime Transport and Logistics Conference

"MARLOG 13"

Towards Smart Green Blue Infrastructure

3-5 March 2024 - Alexandria, Egypt

Ahmad A. Moussa

Teaching Assistant &
Data Analyst

A NOVEL DYNAMICAL ROUTE OPTIMIZATION METHOD TO IMPROVE SHIP'S VOYAGE TIME: TIME BOUNDARY SEMICIRCLES

Ahmad A. Moussa, Amman A. Ali, Ahmed S. Shehata, Mohi El Sayeh

Highlights

- Weather routing optimization advancements
- Knowledge Gap Analysis
- Novel Approach (TBS)
- Validation
- Results

according to topics

Introduction

- Ship Energy Consumption
- Fuel Consumption (Propulsion – Electricity)
- Costs and Emissions
- Weather conditions increase fuel consumption
- Waves, wind, current and other factors

according to
topics

- Notable contributions have been made in this domain
  - neural network model utilizing ship-collected data to predict and evaluate a ship's energy efficiency under varying navigational conditions
  - Three-Dimensional dynamic programming method for ship voyage optimization
  - multi-objective programming model incorporating fuel consumption, fuel price, freight, and inventory costs to optimize route assignment and speed for multiple ships in transit

- solely concentrated on optimizing energy consumption along a specific route.
- previous research has examined optimization outcomes at fixed, predetermined sailing speeds, failing to comprehensively account for the impact of different sailing speeds on optimization results.

- In the past three years, researchers have addressed this issue by conducting studies that focus on a joint optimization approach for sailing routes and speeds. This approach takes into account the interaction between route and speed, along with multiple environmental factors

Gap analysis and Research Aim

- Researchers assumed a constant ship speed during each time step, overlooking involuntary speed reductions caused by added resistance. This oversight impacts the timing of environmental information acquisition for parameter calculations
- The division of time steps is influenced by velocity changes, leading to reduced distances covered within the preset time frame used in calculations. This alteration affects the precision of the model.

- The aim of this paper is to propose new methodology and algorithm to overcome this gap with a more precise perspective and taking into consideration the involuntary speed reduction and time zones through constructing Time Boundary Semicircles (TBS) that ship will not exceed in a preset time frame

Methodology

- **The proposed method comprises four integral components:**
  - Meteorological data acquisition
  - A mathematical model addressing involuntary speed reduction caused by waves
  - Innovative procedures for solution algorithm
  - Test case to compare TBS with prior approved methodology to prove its effectiveness in optimizing voyage time

Meteorological data acquisition

- Copernicus Marine Environment Monitoring Service (CMEMS)

Mediterranean Sea Forecast Module data and properties

Full name	Mediterranean Sea Waves Analysis and Forecast
Product ID	MEDSEA_ANALYSISFORECAST_WAV_006_017
Spatial extent	Mediterranean Sea Lat 30.19° to 45.98° , Lon -18.12° to 36.29°
Spatial resolution	0.042° × 0.042°
Temporal resolution	Hourly
Format	NetCDF-4

Involuntary speed reduction mathematical model

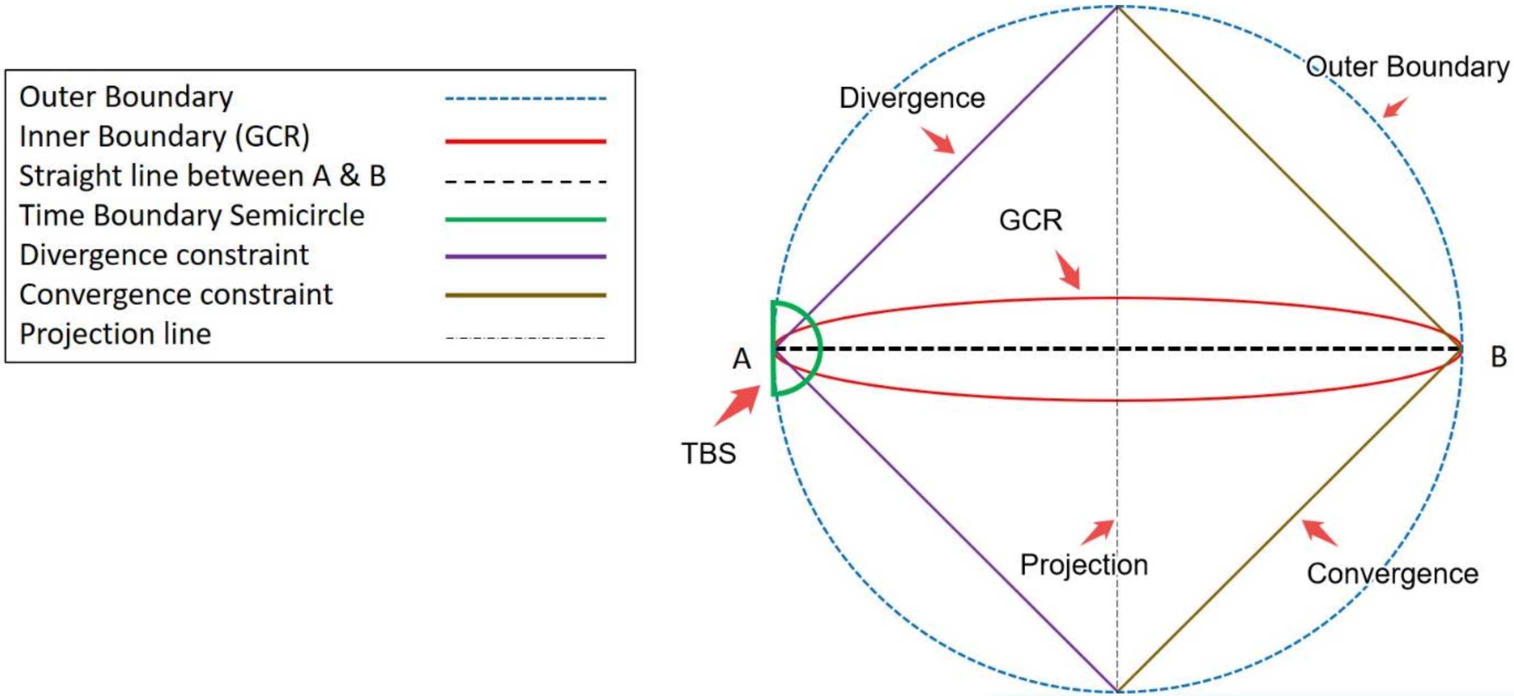
- As a sailing ship contends with wind and irregular waves, the ship's resistance amplifies, diminishing its speed under the consistent power output of the main engine
- This reduction in speed results in a modification of the time intervals for data acquisition
- Consequently, inaccuracies may arise in the weather conditions data provided to the mathematical model and solution algorithm, resulting in errors in the outputs.
- Bowditch's approach

$$V\ (Hs,\ \Theta) = V_o - F\ (\Theta)^*\ Hs^2$$

Θ	F (kn/ft^2)
[0°, 45°]	0.0083
]45°, 135° [	0.0165
[135°, 225°]	0.02480
]225°, 270° [	0.0165
[270°, 360°]	0.0083

Solution Algorithm

- Time Boundary Semicircles (TBS) that ship will not exceed in a preset time frame
- The radius of TBS will be the maximum distance the ship can cover based on her maximum speed in preset time frame
- Zone that contain candidate positions as lat. and long. In which ship can choose to optimize the route
- Environmental conditions will be obtained in this time frame and involuntary speed reduction based on added resistance from waves will be calculated
- Positions with minimum reduction will be chosen to avoid more power and fuel consumption
- Distances will be accumulated and summed based on paths followed
- Time Corrected Value (TCV), When TCV reach preset time frame another TBS will be constructed.


Outer Boundary
Inner Boundary (GCR)
Straight line between A & B
Time Boundary Semicircle
Divergence constraint
Convergence constraint
Projection line
Outer Boundary
Divergence
GCR
A
B
TBS
Projection
Convergence

Line	Procedures of solution algorithm
1	Begin
2	Construct AB line segment between start point and end point
3	R1 = 0.5* AB
4	Construct a Circle with radius R1 passing through A & B (Outer Boundary)
5	Construct GCRs on both sides of AB line segment as (Inner Boundary)
6	Construct Projection Line at midpoint of AB perpendicular to it and intersect Outer Boundary
7	Construct Divergence constraint line segments on both sides, divergence angle = 90^{o} initially
8	Construct Convergence constraint line segments on both sides, convergence angle = 90^{o} initially
9	Construct TBS in the direction of End point with radius R2 = Max. Ship Speed * time frame
10	Calculate involuntary speed reduction at all positions of intersections between long. And lat. inside the TBS using Mathematical model mentioned
11	Adjust divergence and convergence angles based on minimum values of reduction regarding their positions, constraints lines will be drawn and pass with farthest points in both direction
12	Closest node in range of 5 Nautical miles with the min. speed reduction will be chosen as a way point
13	Plot a line segment between this point and next node.
14	Take its distance and append it to one dimensional array of distances between nodes
15	Divide corresponding distances with initial speed (assumed to be maintained constant)
16	Append it to array of TCV
17	Do summation for elements of TCV array
18	If $\sum$ of elements of TCV array $\leq$ 1 hour (preset time frame)
19	Loop from line 10 to line 18
20	Else, stopping criteria is met, identify the current node position
21	Loop form line 9 to 20
22	This loop will continue till the last TBS
23	If the node coincides with the End point
24	STOP

Test Case comparison between TBS and SIMROUTE software

- Hypothetical case study between Start point (A) with coordinates of (40.4833, 2.5) and End point B with coordinates of (40.9833, 3.5) (Mediterranean Sea)
- weather conditions data of this region is downloaded from CMEMS with prespecified parameters known as metadata of the simulation

Data time	21-01-2020
Time resolution	One hour from 00:00 to 23:00
Initial velocity	16 knots
Data boundaries	Lon. Min =1.500 Lon. Max =5.500 Lat. Min = 38.450 Lat. Max = 42.150
Data included	Wave significant height (H_s) in meters Wave Periodic Time (T) in seconds Wave encounter direction in degrees
Involuntary Speed reduction model	Bowditch model
Start time of sailing	00:00

SIMROUTE with A* Algorithm Implementation

- (Grifoll et al, 2022) implemented a comprehensive software for ship weather routing referred to as SIMROUTE
- A* pathfinding algorithm is used to optimize sailing route as a function of the wave action
- This software is opensource and consists of many python scripts to implement weather routing
- To apply this methodology on test case, we Run 3 scripts and import Metadata form separate script named “params” as follows:

- 1- get_waves_CMEMS.py: to download weather data with prespecified parameters

- 2- make_waves.py: this script is used to mesh-grid waves data and construct heatmap with waves significant height for each intersection point between latitudes and longitudes

- 3- main.py: this is the main script that apply A* algorithm and cost function implementation and get out results needed.

TBS Implementation

- Excel software is used with number of iterations as follows:
  - The wave data downloaded in (.nc) format has been converted to CSV format
  - CSV file contains data for 24 hours from 00 to 23 for the data 21-01-2020, so we divide each hourly data in a separate file as a chunk of data, every file includes data for each TBS constructed and used.
  - Starting from 00-hour file data as it is the start of the sailing from A, and after setting the closest range of candidate position to be in range of 5 nautical miles
  - Dead reckoning techniques is used to determine the boundaries of searching the candidate positions around the start point by finding 3 values from start point which are: max_lat. at 0^o, min_lat. at 180^o, and max_long. At 90^o
  - These degrees are measured from north. So, from the start position we add 5 Nm in 3 directions (0, 90, 180)
  - These positions will construct inner semicircle with radius of 5 nautical miles. And within this boundary all candidate positions will be considered.

- Equations used to determine new latitudes and longitudes are as follows:
  - $\varphi_2 = \text{asin}(\ \sin\varphi_1 \cdot \cos\delta + \cos\varphi_1 \cdot \sin\delta \cdot \cos\theta\ )$
  - $\lambda_2 = \lambda_1 + \text{atan2}(\ \sin\theta \cdot \sin\delta \cdot \cos\varphi_1, \cos\delta - \sin\varphi_1 \cdot \sin\varphi_2\ )$
- where φ is latitude, λ is longitude, θ is the bearing (clockwise from north), δ is angular distance d/R; d being the distance travelled, R the earth's radius in nautical miles
- Each new (φ_2, λ_2) will be calculated to get those boundaries
- Based on max_lat. , min_lat., and max_long. filtration of data will take place to determine candidate positions
- After determining candidate positions, involuntary speed reduction calculations are conducted based on the data
- Maximum velocity between candidate positions is chosen as the location of minimum reduction. The coordinates of this position are chosen to be the optimized next waypoint

- By using spherical law of cosines, we determine the distance between current position (start point) and following waypoint
  - Distance = acos(sin(lat1)*sin(lat2) + cos(lat1)*cos(lat2)*cos(lon2-lon1)) * R

- Through this methodology, velocity is assumed to be maintained around the initial velocity, so TCV will be calculated by dividing distance by initial velocity.

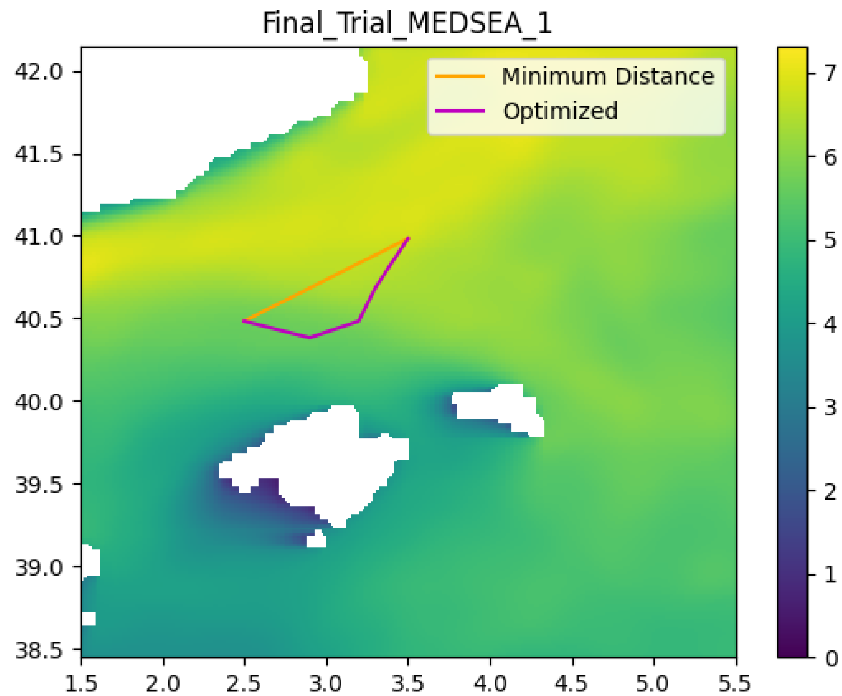
- TCV will be accumulated and summation will take place after every iteration till Σ TCV will exceed 1 hour. Subsequently, the next data file for next hour is used and another TBS will be constructed.

- Convergence and Divergence constraints are adjusted and fitted manually for simplicity in this implementation to ensure arrival to end point.

Results and Discussion

- Results are compared between these 2 methodologies based on 3 criteria:
  a. Sailing distance
  b. Sailing time (main optimization factor)
  c. Optimized route

  – Optimized route that optimize the first route taking into consideration the weather conditions by minimizing cost function that includes many factors for instance, wave effect on navigation, speed reduction and minimum path finding algorithm



- SIMROUTE Algorithm divided the route into 24 waypoints from A to B that means 24 iterations are used to reach the end point

Criteria	Sailed hours	Sailed miles
Route optimized	7.53	67.18
Route Minimum distance	11.29	54.47

- After implementing TBS algorithm using Excel software, we found that 6 TBSs are constructed with total of 20 iterations to reach endpoint B
- Sailing time for the trip between A and B is 5.4631 hours with 2.07 hours saving of time by applying TBS algorithm.
- The total distance travelled is 86.605 nautical miles which is more than SIMROUTE algorithm by 19.425 nautical miles.
- But it is better to choose longer distance with minimized time of arrival and with minimum impact of weather to ensure less fuel consumption and more safety considerations.

- Results show significance of TBS over SIMROUTE with A* Algorithm in minimizing sailing time. Sailing time is minimized by 27.5 % by applying TBS

- This study has some limitations, Excel software usage for implementing the algorithm which has less precision than python programming language, but we choose to use it for its simplicity
- Number of iterations also considered as limitation. By increasing number of iterations and decreasing range of closest distance more precise outputs will be gained. This will be considered for future work

Conclusions

- In this study:
  - TBS novel approach is proposed to cover the gap in the previous academic advancements regarding continuous time varying weather conditions and its impact on prediction of optimized routes.
  - Route is optimized by finding positions (lat., long.) where the weather conditions have the least impact in range of divergence – convergence constraints.
  - Involuntary speed reduction model is chosen (Bowditch) to predict these positions and propose an optimum path consisting of points of least speed reduction
  - Test case between 2 hypothetical positions in Mediterranean Sea has conducted to compare between TBS methodology and previous approved methodology which is SIMROUTE software with A* Algorithm
  - The results confirm the significance of TBS algorithm by reducing sailing time by 27.25 % from the SIMROUTE methodology for the same initial conditions.
  - For future work recommendations, mathematical model used must be developed to comprise wind effect also not only waves effect.
  - Python scripts will be developed to maximize efficiency of TBS algorithm and consider all corner cases.

Acknowledgement

- I would like to express my sincere gratitude to My professors, that guide me through this work and made a substantial contribution to our study. Your excellent help and expertise have added much value to our research.
- Dr/ Amman Ali — Institute of maritime upgrading studies
- Dr/ Ahmad S. Shehata — Marine and offshore engineering department
- Dr/ Mohi El Sayeh — college of maritime transport

I want to sincerely thank you for all your efforts and dedication.

Arab Academy
for Science , Technology and Maritime Transport

13 Marlog 2024

The International Maritime Transport and Logistics Conference

"MARLOG 13"

Thank You