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RETROFIT SOLUTIONS TO ACHIEVE 55% GHG REDUCTION BY 2030

Report of on-board demonstration for weather routing and speed optimisation systems

WP 7 – Technology Demonstration
Task 7.3 – Real demonstration of weather routing system
D7.4 – Report of on-board demonstration for weather routing and speed optimisation systems
Partners involved: SFWD, NTUA, ATD, AES, LASK, CNR, RINA, B4B, AWS
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List of acronyms

2D	Two-dimensional
3D	Three-dimensional
3DDA	3D Dijkstra Algorithm
ETA	Estimated Time of Arrival
FOC	Fuel Oil Consumption
GUI	Graphical User Interface
ME	Main Engine
NTUA_WRT	NTUA Weather Routing Tool
SFC	Ship Fuel Consumption
SFOC	Specific Fuel Oil Consumption
SWH	Significant Wave Height

Nomenclature

$A_{XV}\,[\mathrm{m}^2]$	Transverse projected area above the waterline
$C_{AA}\,[-]$	Wind resistance coefficient
$H_s\,[\mathrm{m}]$	Significant wave height
$P_B\,[\mathrm{kW}]$	Engine brake power
$P_D\,[\mathrm{kW}]$	Propulsion power
$P_E\,[\mathrm{kW}]$	Effective power
$R_{AA}\,[\mathrm{kN}]$	Wind resistance
$R_{APP}\,[\mathrm{kN}]$	Appendage resistance
$R_{AW}\,[\mathrm{kN}]$	The added resistance caused by waves
$R_{CALM}\,[\mathrm{kN}]$	Sum of resistance
$R_{TOTAL}\,[\mathrm{kN}]$	Total resistance
$R_W\,[\mathrm{kN}]$	Wave resistance
$R_{other}\,[\mathrm{kN}]$	Other resistance
$T_p\,[\mathrm{s}]$	Wave peak period
$T_{target}\,[-]$	target arrival time
$V_{WR}\,[\mathrm{m/s}]$	Relative speeds
$V_g\,[\mathrm{m/s}]$	Ground speeds
$\eta_h\,[-]$	Hull efficiencies
$\eta_o\,[-]$	Open water efficiencies
$\eta_r\,[-]$	Relative rotation efficiencies
$\eta_s\,[-]$	Shaft efficiencies
$\rho_A\,[\mathrm{kg/m}^3]$	Air density
$\varphi_{WR}\,[\mathrm{deg}]$	Wind direction
$D(\theta)$	Directional spreading function
$S\,[-]$	Wave spectrum
$V\,[\mathrm{m/s}]$	Given speed
$\beta\,[\mathrm{deg}]$	Relative wave angle
$\rho\,[\mathrm{kg/m}^3]$	Fuel density

Executive Summary

For WP7 of the RETROFIT55 project, two Weather routing tools were developed – one by AALTO and another tool developed by NTUA, each using different methodologies. It has been determined that the on-board demonstration shall be carried out using the NTUA Weather Routing Tool, while optimization scenarios shall be run using the AALTO Weather routing tool, for benchmarking purposes. Results obtained by each weather routing tool have been discussed in detail respectively in Annex I (NTUA) and Annex II (AALTO).

This report documents the activities concerning the demonstration of the NTUA Weather routing tool that has been developed and can be used for the assessment of retrofit measures along specific routes with and without enabling the route optimization functionality. The tool provides a practical solution for route planning under realistic weather conditions, improving operational efficiency and energy savings. It is a MATLAB-based application (also available as a standalone executable) developed to optimize a vessel's voyage with respect to Fuel Oil Consumption (FOC), while accounting for prevailing weather conditions.

The optimization process evaluates multiple candidate routes using Genetic Algorithm (GA), iteratively improving towards the best solution. The algorithm can explore feasible solutions under operational limits and criteria that can also be implemented such as duration/depth limitations, etc.

AALTO presents a three-dimensional weather routing algorithm (3DDA) for the development of AALTO weather routing tool, designed to optimize ship voyages by integrating weather data and detailed ship performance models. Unlike traditional two-dimensional methods that assume constant speed, the 3DDA incorporates time as a variable, enabling dynamic speed or power adjustments to improve efficiency and safety. Using data from an actual long-distance voyage, the report develops a robust evaluation framework that includes resistance models and propulsion energy calculations. Scenario-based simulations demonstrate the 3DDA's ability to deliver globally optimal, fuel-saving routes, achieving 2% to 8% fuel savings under fixed Estimated Time of Arrival (ETA) constraints for the case study voyage. The algorithm also offers flexibility by generating either the fastest or most fuel-efficient routes, depending on operational needs. The results highlight the 3DDA's potential to outperform conventional methods, promoting smarter, safer, and more sustainable ship operations.

The demonstration of the tool was carried out for the case study vessel M/V KASTOR and the ship operator was presented with the results of the weather routing and speed optimization tool. Feedback was obtained for possible improvements and for inclusion of additional features in the tool.

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1 Ship voyage optimization and case study ship

Ship voyage optimization is the process of planning the most efficient sailing route by integrating data such as weather forecasts, ship performance characteristics, operational schedules, and navigational constraints. These inputs are analyzed using advanced optimization algorithms to identify optimal routes that reduce fuel consumption, shorten transit times, and improve arrival time accuracy. The outcome is safer, more sustainable, and cost-effective maritime operations.

This section presents a ship voyage optimization approach using a 3D voyage optimization method. To demonstrate the practicality and effectiveness of the used ship voyage optimization, a series of examples are provided. Among these, a real case study is conducted for the vessel MV KASTOR, whose main particulars are summarized in Table 1. This is a Kamsarmak bulk carrier scheduled to sail from Panama to Mersin, departing on 11 December 2024 at 00:00 and expected to arrive on 25 December 2024 at 13:53. By applying the ship's detailed specifications and the proposed optimization algorithms, the objective is to identify the most efficient voyage plan (minimizing fuel consumption and considering as a constraint the transit time), while ensuring navigational safety and a reliable estimated time of arrival.

Table 1: Ship specification of the Kamsarmak class bulk carrier.

Length overall	229.00 m	
Length between perpendiculars	225.50 m	
Breadth, moulded	32.26 m	
Depth, moulded	20.05 m	
Summer load line draught, moulded	14.45 m	
Deadweight at summer load draught	80996.1 t	
Draft (T)	12.6 m	
Longitudinal Center of Gravity (XG)	-14.1 m	
Block Coefficient (CB)	0.879	
Vertical Center of Gravity (KG)	11.51 m	
Metacentric Height (GM)	2.5 m	

2 Onboard demonstration of weather routing and speed optimization systems

A live demonstration of the weather routing tool was organized at the premises at the LASKARIDIS SHIPPING (Athens, GREECE) on Tuesday, 15th April 2025. The demonstration was conducted at the operations centre of the ship operator, where real-time information for all vessels of the fleet is on display. The meeting was attended by the following persons:

- Christopoulos Georgios, Chief Operating Officer (LASK)
- Tsoulakos Nikolaos, Innovation & Technology Manager (LASK)
- Giannakakis Myron, Chief Data Analyst (LASK)
- Seferlis Konstantinos, Performance Operator (LASK)
- Nikos Themelis (NTUA)
- Aggeliki Kytariolou (NTUA)
- George Dafermos (NTUA)

Figure 1: Persons present at the on-site demonstration of the weather routing tool.

Also attending the meeting remotely were the Master & Chief Engineer of the vessel M/V KASTOR, who had also been provided a copy of the weather routing tool, so that they could also run the tool at their end.

The aim of the meeting was the demonstration of the installation and use of the Weather Routing tool developed by NTUA. Firstly, Nikos Themelis (NTUA) and Nikos Tsoulakos(LASK) presented the aim of this task and specifically of the demonstration. Then, Nikos Themelis briefly discussed the key elements of the Weather Routing tool and proceeded with a live demonstration.

The software was successfully installed on a laptop, on-site. NTUA has prepared a user guide, which is provided in Annex III, to support the usage of the tool. Furthermore, the installation package was also distributed to LASK members who joined the meeting. After completing the installation, Aggeliki Kytariolou (NTUA), presented the Weather Routing tool utilization, by setting up a demonstration case study for M/V KASTOR regarding a past voyage that took place in December 2024. Following the launch of the software, the Graphical User Interface (GUI) was initiated, and the input arguments were explained to the partners and suitably completed. Subsequently, the weather routing optimization was launched through the GUI window and after waiting for a few minutes, the results were generated.

The output was generated and comparisons between the optimal route and the orthodrome were presented in the GUI window showing potential for main engine fuel oil consumption reduction of about 5.5%, compared to the orthodrome route. Furthermore, results referring to the data regarding the ship operational and weather conditions, on a daily basis were also shown in the software window and respective explanations were given. Finally, the generated html-report summarizing the results was also shown (a sample report is provided in Annex IV), by using a simple pre-installed web browser. In addition, several demonstration cases were examined corresponding to different vessel speeds and voyage durations accounting for selected delay tolerances with respect to the corresponding Estimated Time of Arrival (ETA) along the orthodromic path.

3 Feedback obtained & suggestions for further development of the tool

Members from LASK present at the demonstration understood the basic function of the weather routing tool and recognized the potential it could have in increased fuel savings, if used on a larger scale, also on other vessels of their fleet. A few queries were raised regarding user input, methodology used by the tool in finding an optimal route, as well as regarding the report generated by the tool, but overall, the attendees found the operation of the tool simple. Nikos Themelis mentioned that the theoretical background of the tool has been presented in detail in D3.2.

It was pointed out to all attendees that by using different values for input parameters (Vessel speed, delay tolerance, etc.), a wide range of scenarios could be obtained. The users shall progressively gain experience on the use of the tool, allowing them to obtain a better understanding of these parameters and how they affect the final output, and they shall thereby be able to restrict the number of possible outcomes to only the meaningful ones.

During the meeting, discussion regarding the potential of the weather routing tool and its practical applicability was carried out. Feedback regarding the manner in which such weather routing tools are utilized by the operational department of the shipping company, in collaboration with the charterer, was also provided by the partners, providing further insight into the weather routing optimization from a practical point of view.

A few general questions were raised, especially by the Master of the vessel, about general operation of the tool and these were promptly answered by members of NTUA. Nikos Tsoulakos stated that this was a good starting point and if developed further, by incorporating more parameters, and providing higher fidelity, could prove to be quite beneficial in the long run. A few other general ideas were suggested to further improve the weather routing tool, as part of future work.

User feedback from attending persons of LASK was obtained by means of a questionnaire. This has been included under Annex V of this report.

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[4] Chen, Y., Zhang, C., Guo, Y., Wang, Y., Lang, X., Zhang, M., & Mao, W. (2025). State-of-the-art optimization algorithms in weather routing—ship decision support systems: challenge, taxonomy, and review. Ocean Engineering, 331, 121198.

[5] RETROFIT55 – Deliverable 3.2 - Integration of the ship model in weather routing

Annex I – Weather Routing Optimization Cases (NTUA)

Voyage: Panama – Mersin [11/12/2024 0:00 - 4/1/2025 0:00]

Optimization: Panama – Check Point* [11/12/2024 0:00 – 27/12/2024 11:23]

Coordinates for Panama: 9.2697 -79.9233

Coordinates for Check Point: 35.8554 -8.0425

*Open ocean area selected for demonstration purposes.

According to noon reports, the total Fuel Oil Consumption recorded from 11/12/2024 00:20 until 27/12/2024 12.00 was 392.35t.The total Fuel Oil Consumption is the aggregate of, 348.85t that were consumed by the Main Engine and another43.5t consumed by the diesel generators. The average speed of the vessel along the voyage was 10.7kn, varying from 8.8 to 11.9kn.

Based on the noon reports and the available high frequency data, the vessel's actual route on 11.12.2024 at 00.00 closely aligns with the orthodromic path (Figure 2) connecting the port of Panama and the selected destination point west of Gibraltar. The actual distance covered is 4208.6nm, while the othodromic path is 4199nm long. The difference is negligible and therefore, for the analysis presented below, the orthodrome is selected as a reference instead of the actual path (same approach adopted in the DEMO presented to the partners).

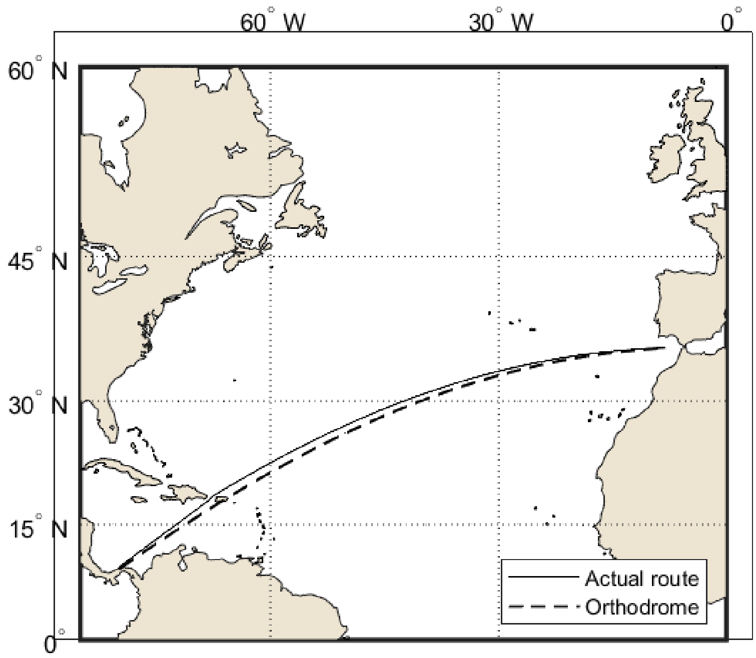


Figure 2: Close alignment between actual route and orthodrome.

Optimization case 1

According to noon reports, the average speed of the vessel along the voyage is 10.7kn. Nevertheless, the orthodrome was simulated using the NTUA Weather Routing Tool to estimate the

Fuel Oil Consumption of the Main Engine and to serve as a reference for the upcoming optimization. A maximum duration of 16.5 days was also imposed to roughly match the actual ETA. Under this constraint, the required constant speed for the simulated orthodromic path is 10.6kn. For the optimization, the same constant speed is assumed. Additionally, an allowable tolerance in voyage duration is introduced, allowing the optimal voyage duration to exceed the orthodrome's duration by no more than 5 hours. Results are shown in Table 2:

Table 2: Results for CASE 1 optimization

	Distance [nm]	ETA [days]	ME FOC [t]
Orthodrome	4199	16.5	279.7
NTUA_WRT	4229.4	16.6	270.1
Diff [%]	+0.72	+0.72	-3.43

It is obvious that simulated results regarding the orthodrome and consequently the actual route, are not in accordance with reported FOC in noon reports (348.85t). Calculations performed with the NTUA Weather Routing Tool are based on a physics-based model employing empirical formulas assuming ideal conditions such as clean hull and propeller. However, in real sea conditions, the vessel does not operate under ideal conditions and also travels at varying speed, rather than the constant one assumed during the simulation.

In Figure 3 and Figure 4, the required ME Power and the prevailing significant wave height along the orthodrome and the optimal path are presented respectively. In addition, in Figure 5, the two paths are plotted on a Mercator map.

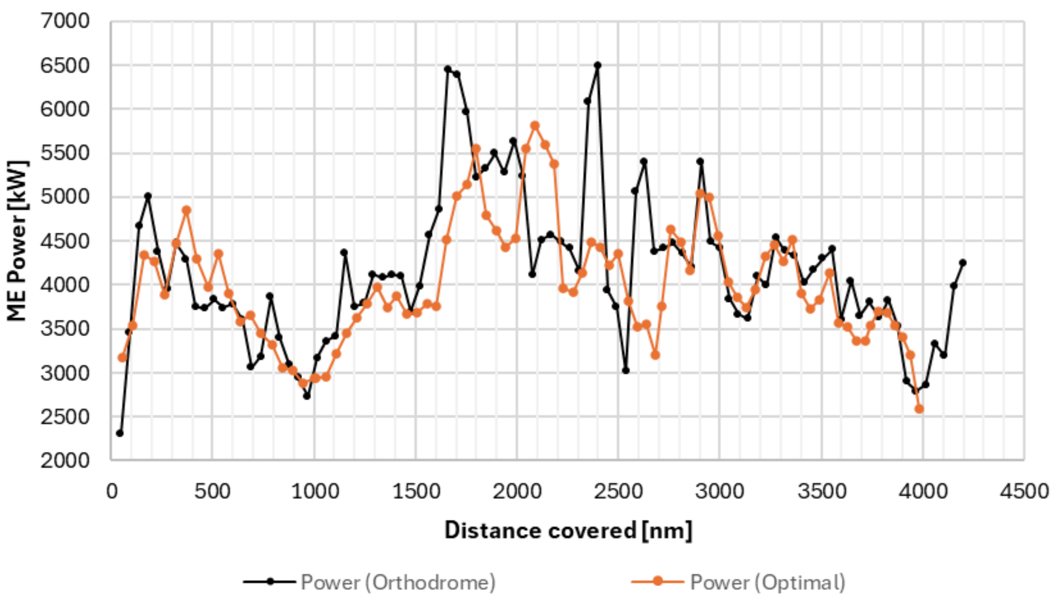


Figure 3: Required ME Power along the orthodromic and the optimal path.

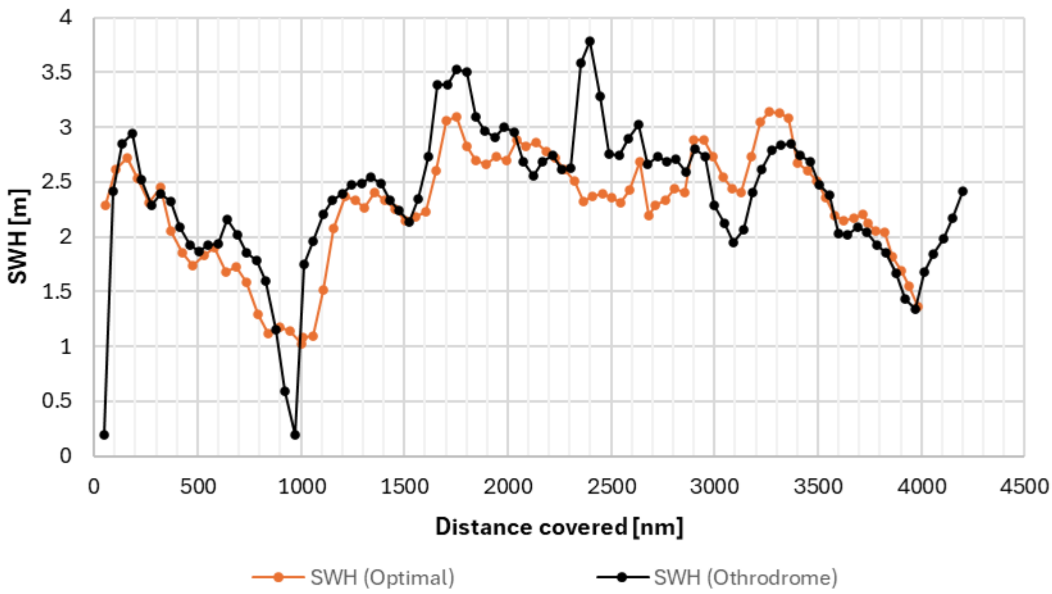


Figure 4: Significant wave height alone the orthodromic and the optimal path.

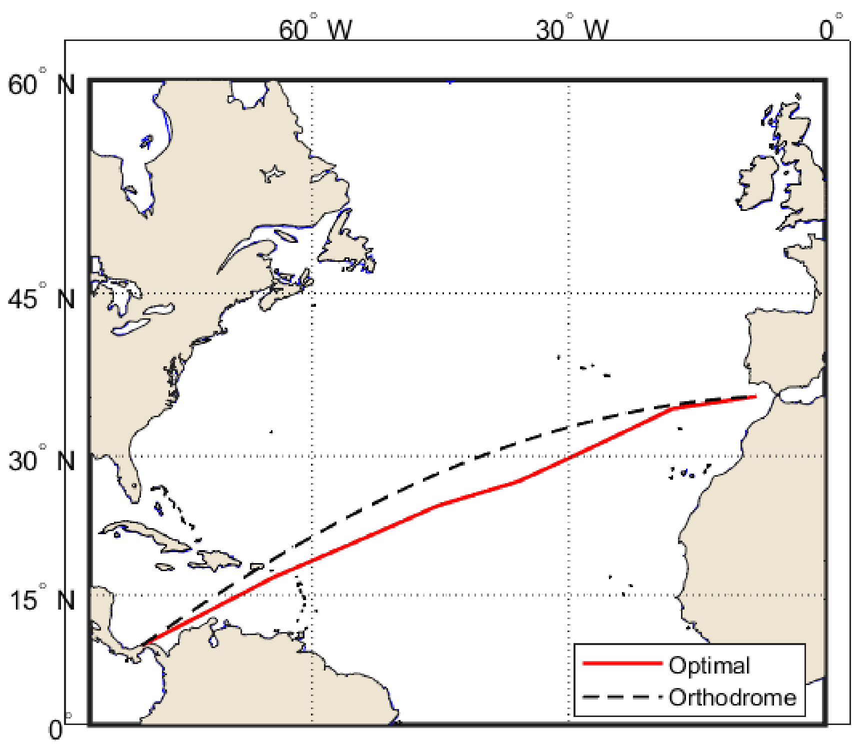


Figure 5: Mercator map presenting the orthodrome and the optimal route for CASE 1.

Optimization case 2

To investigate gains from the optimization process a second case is examined assuming vessel speed increase at 12kn, while the allowable voyage duration remains the same as in CASE 1. The results are presented in Table 3, presenting a comparison between the optimal path and the shortest one, which is the orthodrome.

Table 3: Results for CASE 2 optimization.

	Distance [nm]	ETA [days]	ME FOC [t]
Orthodrome	4199	14.58	350.88
NTUA_WRT	4251	14.76	328.89
Diff [%]	+1.23	+1.23	-6.26

Moreover, in Figure 6 and Figure 7, the ME Power and the significant wave height along the two paths under comparison are shown, while in Figure 8, they are illustrated on a mercatoric map.

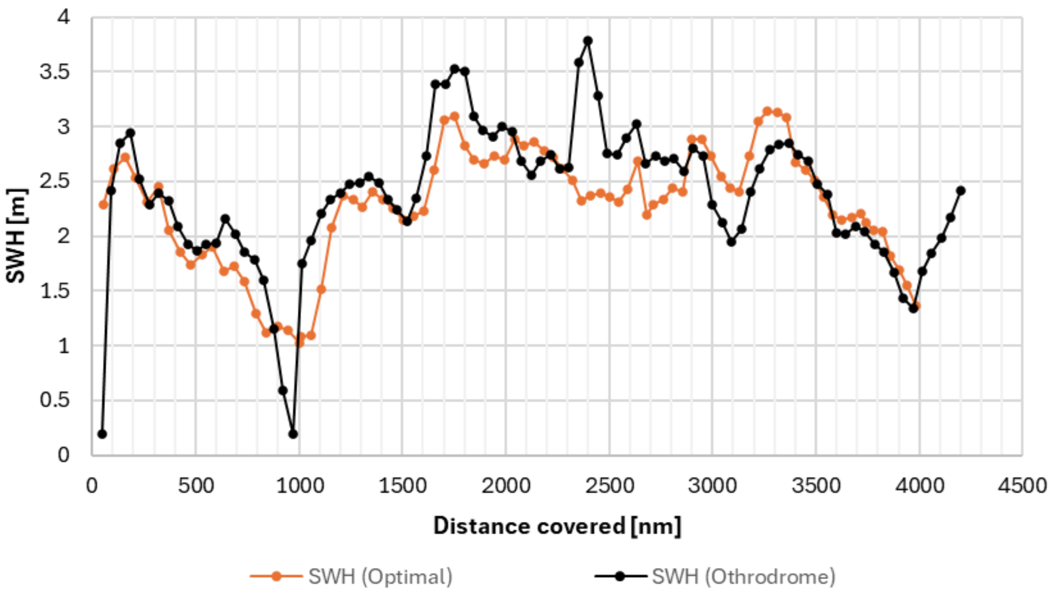


Figure 6: Required ME Power along the orthodromic and the optimal path.

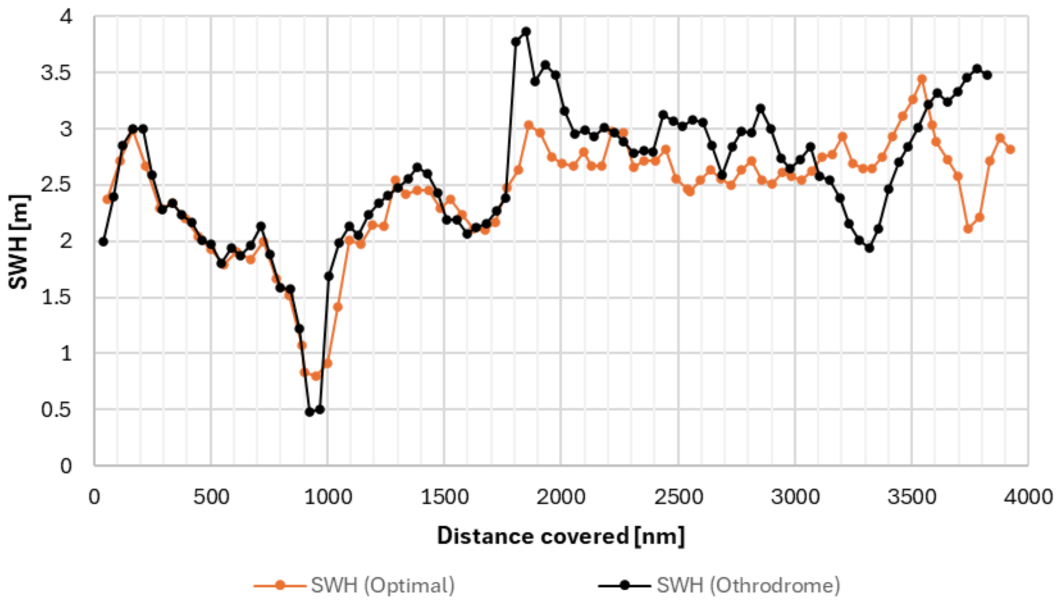


Figure 7: Significant wave height alone the orthodromic and the optimal path.

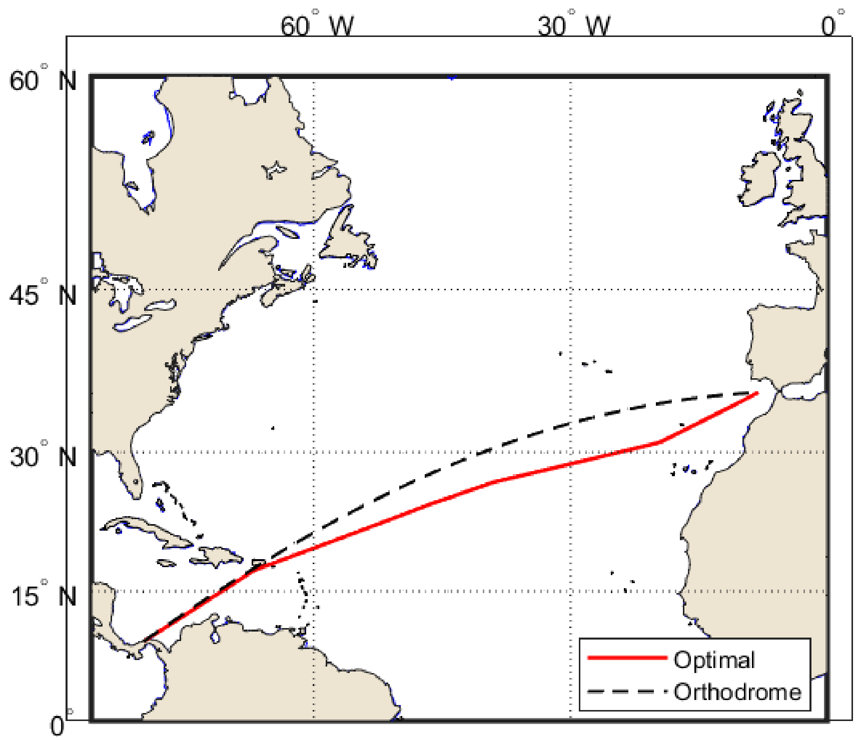


Figure 8: Mercator map presenting the orthodrome and the optimal route for CASE 2.

Annex II – Ship Performance model using Weather Routing Optimization Cases (AALTO)

Ship performance characteristics representation plays a vital role in weather routing. Figure 9 presents the flowchart of semi empirical model for the ship performance estimation. In navigating real sea conditions, ship fuel consumption is influenced by several variables, including engine parameters, propeller characteristics, and the resistance experienced by the vessel. Ship propulsion power correlates closely with its velocity and the encountered operational conditions. The conventional estimation of ship propulsion power and fuel consumption involves sequentially calculating resistance and power requirements. Resistance at varying speeds is determined through model testing, computational methods, or semi-empirical formulations. Additional resistance induced by wind and waves, typically encountered during most voyages, is integrated into the total resistance calculation. This resistance must be counteracted by the propulsive force, which is derived from the ship's engine power transmitted through the propeller system.

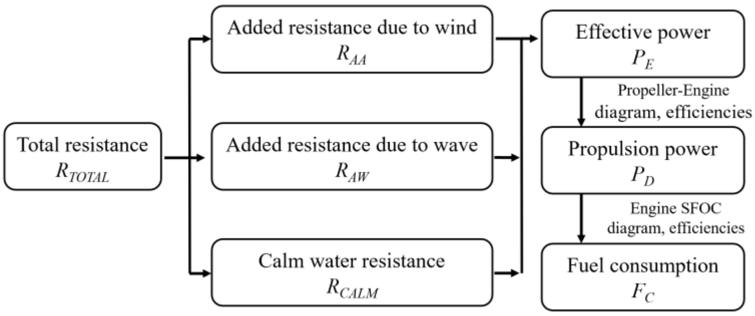


Figure 9: Flowchart of semi-empirical model for the estimation of ship performance

The total resistance in real seaways can be determined as the sum of calm water resistance, wind-induced resistance, and wave-induced resistance. An approximate method was proposed for evaluating resistance in calm water based on ship geometry, appendages, and immersion characteristics (Eq. 1). This resistance (R_{CALM}) is the sum of several components:

$$R_{CALM} = R_F(1 + k_1) + R_{APP} + R_W + R_{other} \quad \text{Eq. 1}$$

Here, R_F is the frictional resistance determined using ITTC-1957 standards. The remaining components, including appendage resistance (R_{APP}), wave resistance (R_W), and others (bare hull, bulbous bow, immersed transom, and model ship correlation resistance), are estimated via empirical formulas or test data, which may offer greater accuracy for specific ship types. In this study, appendage resistance (R_{APP}), wave resistance (R_W), and R_{other} was calculated based on the test data of the case study ship.

Resistance caused by wind depends on the superstructure exposed area and relative wind conditions. Using the ISO (2015) guideline, the wind resistance (R_{AA}) is calculated as:

$$R_{AA} = \frac{1}{2}\rho_A\left[C_{AA}(\varphi_{WR})A_{XV}{V_{WR}}^2 - C_{AA}(0)A_{XV}{V_g}^2\right] \quad \text{Eq. 2}$$

Here, ρ_A denotes air density, A_{XV} represents the transverse projected area above the waterline, and V_{WR} and V_g are the relative and ground speeds, respectively. C_{AA} is the wind resistance coefficient adjusted for the wind direction (φ_{WR}).

The added resistance caused by waves (R_{AW}) integrates wave spectrum data with transfer functions. For irregular seas, it is expressed as:

$$R_{AW}\left(\omega|H_s,T_p,\gamma,V,\beta\right) = 2\int_0^{\infty}\int_{-\frac{\pi}{2}}^{+\frac{\pi}{2}} S\left(\omega|H_s,T_p,\gamma\right)\frac{R_{aw}(\omega|V,\beta)}{\zeta_a(\omega)^2}D(\theta-\beta)d\theta d\omega \qquad \text{Eq. 3}$$

Here, S is the wave spectrum characterized by significant wave height (H_s) and peak period (T_p), β denotes the relative wave angle, and D(θ) represents a directional spreading function.

$$S\left(\omega|H_s,T_p,\gamma\right)D(\theta) = \frac{320{H_s}^2}{T_p^4\omega^5}exp\left(\frac{-1950}{{T_p}^4\omega^4}\right)\gamma^{exp\left[\frac{-(\omega-\omega_p)^2}{2\sigma^2\omega_p^2}\right]}D(\theta) \qquad \text{Eq. 4}$$

$$D(\theta)=\begin{cases}\frac{2}{\pi}\cos^2(\theta) & \text{for } -\frac{\pi}{2}\le\theta\le\frac{\pi}{2}\\ 0 & \text{otherwise}\end{cases} \qquad \text{Eq. 5}$$

Based on the total resistance calculated by Eqs. (2-5), the effective power (P_E) needed to overcome the total resistance (R_{TOTAL}) at a given speed (V) is defined as Eq. (6). The relationship between engine brake power (P_B), propeller efficiency, and effective power is expressed as Eq. (7).

$$P_E = R_{TOTAL}\cdot V \qquad \text{Eq. 6}$$

$$P_B = \frac{P_D}{\eta_s} = \frac{P_E}{\eta_s\cdot\eta_h\cdot\eta_r\cdot\eta_o} \qquad \text{Eq. 7}$$

Here, P_D represents propulsion power, while η_s, η_h, η_r, and η_o denote efficiencies related to the shaft, hull, relative rotation, and open water, respectively. By incorporating specific fuel consumption (SFOC) and operational duration, fuel usage can be estimated for various conditions. In this study, the above parameters were collected based on ship sailing data of the case study ship mentioned.

Finally, ship fuel consumption can be determined by Eq. (8).

$$SFC = \frac{3600\times P_B\cdot SFOC}{1000\times\rho} \qquad \text{Eq. 8}$$

The unit of SFC is L/h (liters per hour). ρ is fuel density. SFOC is typically expressed in grams of fuel consumed per kilowatt-hour (g/kWh) of energy produced by the engine.

3D-method for voyage optimization

The introduction of 2D and 3D methods for voyage optimization

Traditional weather routing methods are primarily based on two-dimensional optimization algorithms, which assume constant ship speed and seek optimal paths only in the latitude-longitude plane. Techniques such as Dijkstra's algorithm, Isochrone methods, dynamic programming, and genetic algorithms have been widely applied in commercial routing software **Error! Reference source not found.**. However, these methods face several limitations: they cannot adjust speed dynamically in response to changing weather, are prone to local optimal solutions, perform poorly on long voyages where weather evolves significantly, and lack direct control over arrival times (i.e., Estimated Time of Arrival), often requiring repeated adjustments to achieve time-specific goals, as shown in Figure 10.

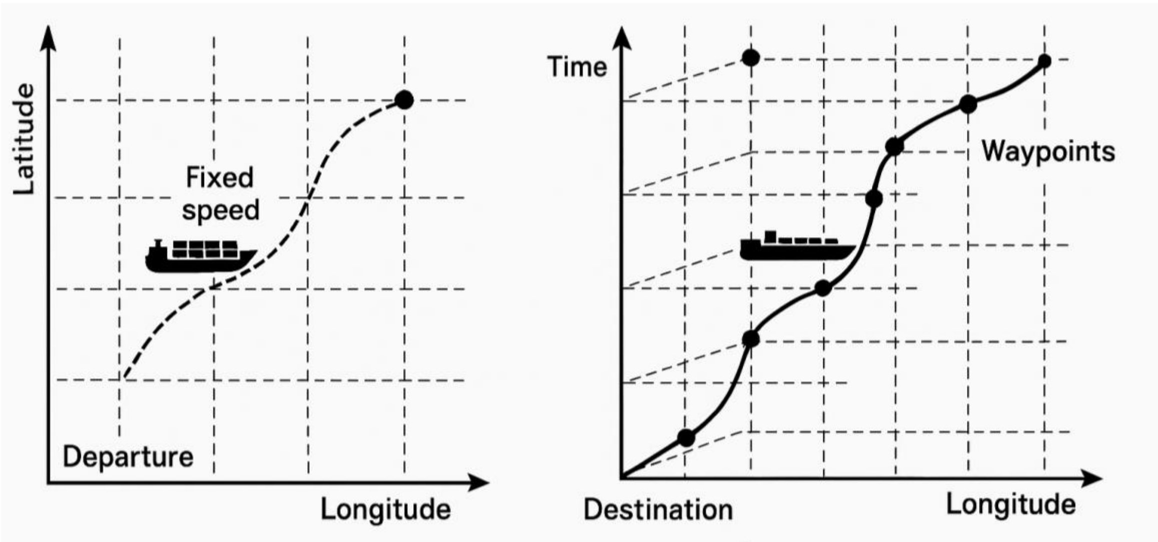


Figure 10: 2D and 3D voyage optimization methods (left: 2D, right: 3D)

To overcome these limitations, three-dimensional voyage optimization algorithm incorporates time as a third dimension. In this algorithm, each point on the route includes both its geographic position and the corresponding arrival time, enabling flexible speed adjustments throughout the voyage, aiming to establish a technical framework for 3D routing, build accurate ship performance models, and develop a time-dependent Dijkstra algorithm to solve for globally optimal routes. Real validations, such as the MV KASTOR case, demonstrate the method's ability to reduce fuel consumption, improve ETA accuracy, and enhance resilience to adverse weather, supporting the broader goals of green and intelligent shipping.

3D Dijkstra algorithm

Building on the 2D geographic space, this adopted method introduces "time" as a third dimension, recognizing that arriving at the same location at different times may result in encountering very different weather and sea conditions. As a result, the cost of traveling along the same geographic path may vary significantly depending on timing. 3D algorithm constructs a three-dimensional weighted graph, where each node is represented as a triplet (longitude, latitude, time). Directed edges between nodes represent feasible transitions—i.e., the ship moving from one location to another within a given time interval—and each edge is assigned a weight such as fuel consumption or travel time. The algorithm searches this 3D graph to find the path with the lowest total cost, as shown in Figure 11.

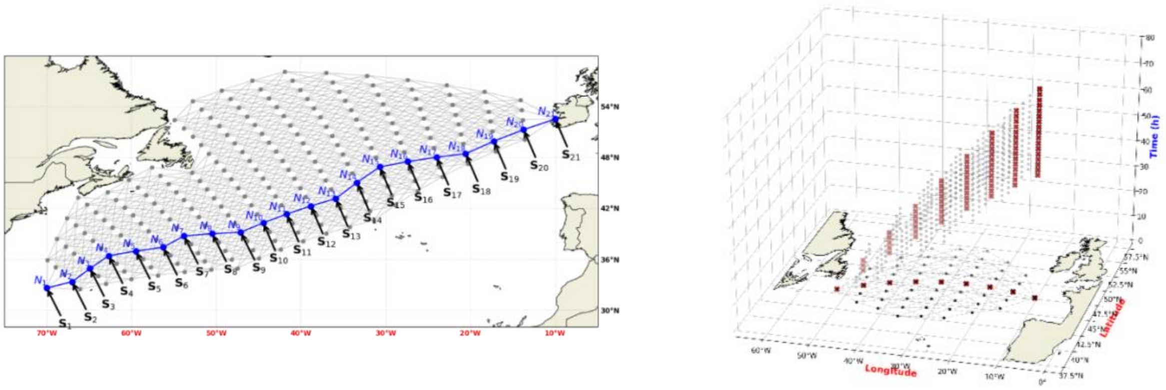


Figure 11: 2D and 3D voyage optimization methods (Left: 2D, right: 3D)

The main advantage of this 3D optimization approach is its ability to optimize both route and speed simultaneously, enabling truly globally optimal solutions. By incorporating time into the state space, the algorithm can dynamically adjust the ship's speed to avoid rough weather or high resistance zones, improving both safety and comfort. It also enables precise control of ETA, which enhances the reliability of fleet scheduling. The model, illustrated in Figure 12, discretizes the voyage into multiple stages, each containing spatial grid points and associated arrival times. Speed optimization is embedded in the pathfinding process: by varying travel time between nodes, the algorithm implicitly adjusts speed—for example, slowing down in rough conditions to reduce resistance and fuel use, or speeding up in calm seas to recover time. This flexibility, unachievable in constant-speed 2D models, allows for generating multiple optimized route plans for different ETAs in a single run. While adding the time dimension increases computational complexity, the project balances accuracy and efficiency by tuning spatial and temporal resolution. The full algorithmic process, from network construction to weight calculation and final path selection, is carefully designed to reflect real-world operational constraints while delivering energy-efficient routing solutions.

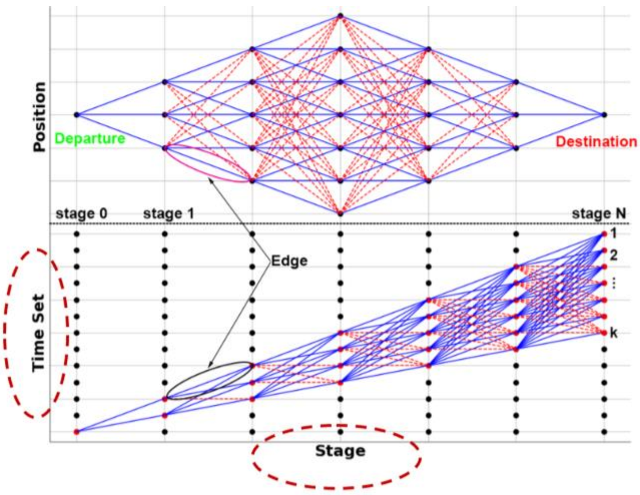


Figure 12: Three-dimensional Dijkstra algorithm

This section details the design and implementation of a 3D voyage optimization algorithm, focusing on the structure of the extended 3D Dijkstra algorithm, the construction of the time-space graph model, and specific improvements developed in this project. The classical Dijkstra algorithm, used to find the shortest path from a source node in a graph, is adapted here to operate over a 3D spatial-temporal network, where each node is defined as a triplet (i, j, t_k), representing a geographic position at a specific voyage stage and time. The objective is to minimize fuel consumption while ensuring arrival by a given ETA. The algorithm accounts for realistic constraints such as ship speed limits, safe navigation zones, and discretized time intervals. Unlike the traditional 2D approach, the 3D version must manage multiple possible arrival times at each location, requiring enhanced data structures to track and update the optimal cost for each (position, time) state.

The algorithm proceeds through the following main steps:

1) Initialization: Set the cost of the departure state to zero and initialize all other states to infinity. Insert the starting state into a priority queue (min-heap).
2) Extract-Min: Repeatedly extract the state with the lowest cost from the queue. If this state has already been finalized, skip it; otherwise, mark it as finalized. If this is the destination state with the required ETA, the algorithm terminates.
3) Relaxation: For each feasible neighboring state in the next stage, calculate the new cost (e.g., fuel consumption) from the current state. If this cost is lower than the current recorded value for that neighbor, update it and insert the state into the queue.
4) Loop: Repeat the extract-relax cycle until the destination state is finalized or the queue is empty.
5) ETA Constraint Handling: Ensure that only paths arriving no later than the target ETA are considered. Nodes exceeding the ETA are pruned during search to ensure feasibility.
6) Backtracking: Once the destination is reached, reconstruct the full optimal path using predecessor pointers, producing a complete route and speed schedule, along with total distance, time, and fuel use.
7) Through this process, the algorithm generates globally optimal routes that are both fuel-efficient and schedule compliant. It has been validated through benchmark cases and shows strong alignment with real-world routing solutions.

Navigational modeling and constraints

In addition to algorithmic design, effective voyage optimization must account for several real-world operational constraints and assumptions in the modeling process:

1) Ship Speed Limits: The algorithm enforces physical bounds on sailing speed. For instance, in this project, the bulk carrier under study typically operates at an economical speed of around 12 knots, with a minimum of approximately 8 knots and a maximum near 14 knots. Any speed outside this range is considered infeasible and excluded from the solution space.

2) Safe Navigational Zones: Based on known sea routes and nautical charts, the model excludes land masses, shallow waters, and environmentally sensitive regions. No feasible nodes or path connections are generated within these restricted areas, ensuring the optimized route remains within safe waters.

3) Turning and Inertia Simplifications: To reduce computational complexity, it is assumed that the vessel can adjust its heading and speed instantaneously at each stage node. Acceleration and deceleration times are neglected. However, to maintain realism, the model imposes a maximum allowable turning angle between adjacent segments, preventing impractical sharp turns.

4) Weather Forecast Accuracy: The optimization assumes that weather forecasts remain accurate throughout the voyage. Although real-world systems may update forecasts and recompute routes periodically, forecast uncertainty is not considered in this study.

With this model in place, the algorithm can accurately estimate fuel consumption and voyage time for any given route and speed profile. The model has been validated under typical sailing conditions and shows good agreement with real-world performance data, providing a solid foundation for optimization and decision-making.

ETA constraint handling

To ensure that the computed route satisfies a given ETA, the algorithm incorporates explicit time constraints during the search process. If the target arrival time is T_{target}, the algorithm restricts consideration to destination nodes (Stage N) whose associated time coordinates do not exceed T_{target}. This is achieved by narrowing the allowable time window at the final stage. Additionally, during the relaxation step, any partial path that leads to a state already exceeding the ETA is pruned from further expansion. This approach guarantees that the final output path adheres to the required arrival time. If multiple ETA scenarios need to be evaluated, the algorithm can either be rerun with different T_{target} values or be configured to retain cost records for multiple destination time states in a single execution. The chapter explores both scenarios: optimizing routes under strict ETA conditions and analyzing the fuel-saving potential when the ETA constraint is relaxed.

Real demonstration cases

To validate the performance of the proposed algorithm, this chapter presents simulation tests based on a real-world oceanic route and a typical vessel type. The experiments are designed to cover different levels of spatial discretization and various optimization objectives, enabling a comprehensive evaluation of the algorithm's effectiveness in terms of fuel efficiency, voyage time, and adverse weather avoidance.

The selected case study is the route from Panama to Mersin, which spans approximately 7,870 kilometers, crossing both the Atlantic Ocean and the Mediterranean Sea, with a typical voyage duration of around 16.5 days. This route was chosen for two key reasons: (1) its considerable length and coverage of multiple meteorological zones make it representative and challenging; (2) actual voyage data from late 2024 is available for MV KASTOR, a Panamax bulk carrier, enabling direct performance comparison. The vessel's design speed is approximately 14 knots, and its service speed is around 12 knots. Ship performance (A resistance and fuel consumption model) was constructed based on ship data.

To assess the algorithm's performance, demonstrations define four experimental scenarios (Cases):

1) **Case 1:** Stage = 80, ETA = 397.5 hours (matching the actual voyage duration). This serves as a baseline scenario, using a coarser stage resolution similar to commercial routing software. The objective is to test whether the algorithm can reproduce the real route and possibly achieve minor improvements.

2) **Case 2:** Stage = 120, ETA = 397.5 hours. By increasing the number of stages (finer spatial discretization), this scenario allows more optimization freedom while keeping the same ETA, aiming to find a more fuel-efficient path.

3) **Case 3:** Stage = 120, minimum voyage time (no ETA constraint). This scenario prioritizes speed over fuel economy, representing an emergency or time-critical operation to evaluate the trade-off in fuel cost.

4) **Case 4:** Stage = 120, minimum fuel consumption (ETA extended by 18 hours to 416.25 hours). Here, the ETA constraint is relaxed to explore the potential for maximum fuel savings with a slightly delayed arrival.

Each scenario is analyzed by comparing the algorithm-generated route with the actual voyage data. Output metrics include the optimized route, segment-by-segment speeds, total voyage time, and total fuel consumption. Key evaluation indicators include: total route distance (km), sailing time (h), fuel consumption (tons), maximum wave height encountered, and cumulative time spent in severe sea states. Of particular interest are the fuel savings rate and arrival time variation. Furthermore, comparisons with the actual route will highlight the algorithm's ability to avoid storms—such as whether it chooses to detour or reduce speed in rough weather zones.

Case 1 – Actual route vs. 3DDA path (stage = 80, ETA unchanged)

Under the conditions of 80 voyage stages and an ETA identical to the actual voyage, the 3DDA produces a route that is nearly identical to the ship's real-world path. As shown in Figure 13, the comparison of the two routes highlights minimal deviation—the red line represents the 3DDA-optimized route, and the gray line shows the actual route. Both paths depart from Panama, cross the Atlantic Ocean, pass through the Strait of Gibraltar, and enter the Mediterranean Sea en route to the Port of Mersin. The total route deviation is less than 1 kilometer, confirming the algorithm's capability to accurately replicate commercially planned paths under coarse discretization and tight ETA constraints.

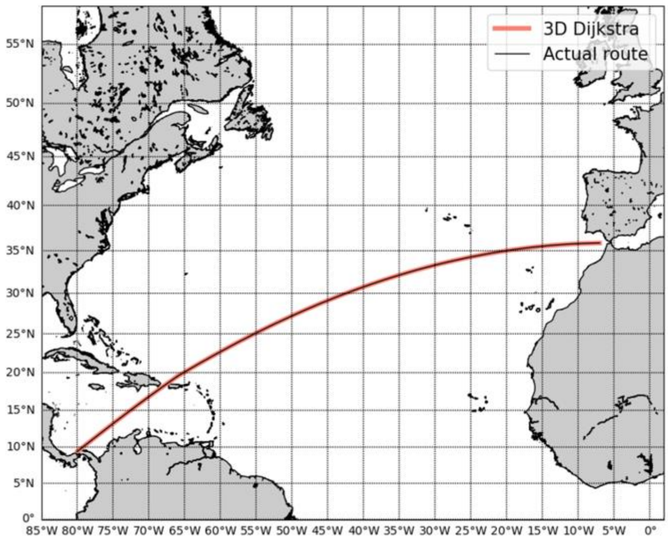


Figure 13: Route comparison in case 1 (the red line represents the 3DDA-optimized route, while the gray line shows the actual route).

As shown in Table 4, both the actual and optimized routes cover 7870 km, with voyage durations nearly equal—397.5 hours and 397.75 hours, respectively. The optimized route achieves a slight fuel saving of about 2 tons, representing a 0.5% reduction. Due to the coarse stage resolution and strict ETA requirement, the algorithm had limited room for improvement, but it still managed to achieve minor fuel savings through subtle speed adjustments. This result demonstrates two important points: (1) the 3DDA algorithm faithfully replicates human-planned routes when optimization flexibility is low, and (2) its performance is at least on par with traditional weather routing methods, with no compromise in fuel efficiency or timing.

Table 4: Route performance comparison (Case 1).

	Distance [km]	ETA [h]	Fuel consumption [tons]
Actual route	7870	397.5	383
3DDA	7870	397.75	381

To further illustrate how the 3DDA path aligns with the actual voyage throughout the route, Figure 14 presents a comparison of ship speed and encountered wave heights along the journey. The top plot shows the variation of speed (in knots) with longitude, while the bottom plot presents the corresponding significant wave height. The results show a high degree of overlap: both routes reduce speed in regions of rough weather (notably between 20°W and 40°W) and accelerate again in calmer conditions to stay on schedule. Since the two routes traverse nearly identical meteorological zones, their wave exposure patterns also closely match. The similarity in speed profiles implies similar engine power demands, confirming that the optimized path mirrors the captain's actual decisions—adjusting speed dynamically to meet the ETA while avoiding weather-induced discomfort. Minor fuel savings likely stem from small-scale power optimizations, such as speeding up slightly earlier when weather conditions ease, or delaying deceleration to better align with the engine's fuel efficiency curve.

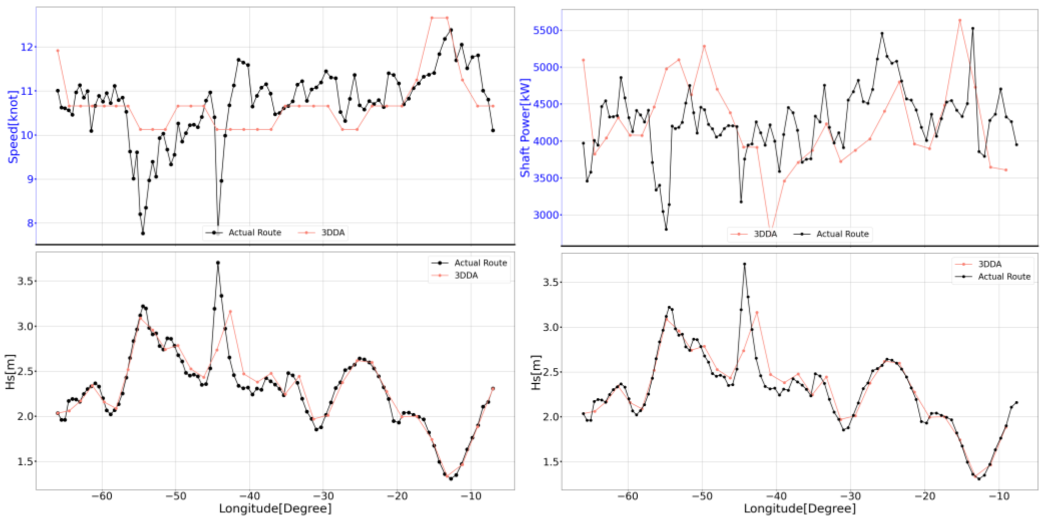


Figure 14: Speed, power and wave height comparison along the route (Case 1: Black: actual route; red: 3DDA optimized route. Both routes slow to under 9 knots around -50° longitude due to high waves, and later accelerate in calmer seas.)

In summary, Case 1 validates the correctness and robustness of the 3DDA algorithm. When constrained to the same ETA and coarse discretization, it accurately replicates the actual voyage path and achieves minor fuel efficiency improvements. This establishes a solid foundation for exploring greater optimization potential in more flexible scenarios.

Case 2 – Energy optimization with finer discretization (stage = 120, ETA unchanged)

In this scenario, the number of voyage stages is increased to 120, improving the spatial resolution by 50% and reducing the time step accordingly. This gives the algorithm greater flexibility in adjusting both route and speed, while maintaining the same ETA of 397.5 hours as in the actual voyage. The optimized result reveals a route that slightly diverges from the actual path across the mid-Atlantic, leading to a notable reduction in fuel consumption, as shown in Figure 15.

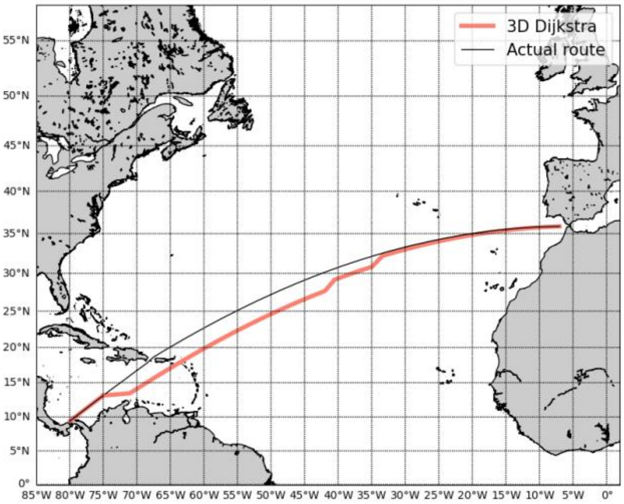


Figure 15: Route comparison in case 2 (the red line represents the 3DDA-optimized route, while the gray line shows the actual route).

The above figure shows a comparison between the 3DDA-optimized route (in red) and the actual route (in gray). In the longitude range from approximately –60°W to –30°W, the optimized route shifts slightly north of the actual track. This deviation allows the vessel to avoid the core of a storm system—even though the route becomes marginally longer (by about 70 km), it stays within the same overall corridor. Post-voyage weather data indicate that a cyclonic storm occurred around 40°W, 35°N in late November. The actual route passed directly through this area, while the 3DDA path preemptively detoured to the north, thereby avoiding the roughest sea conditions. According to Table 5, the optimized route distance is approximately 7698 km, about 2.2% shorter than the actual route, possibly due to a more direct great-circle trajectory, even with the minor detour. Voyage time remains essentially unchanged at 397.75 hours, but fuel consumption drops to 375 tons, a reduction of 8 tons or about 2.1% compared to the actual route—significantly higher than the 0.5% improvement seen in Case 1.

Table 5: Route performance comparison (Case 2).

	Distance [km]	ETA [h]	Fuel consumption [tons]
Actual route	7870	397.5	383
3DDA	7698	397.75	385

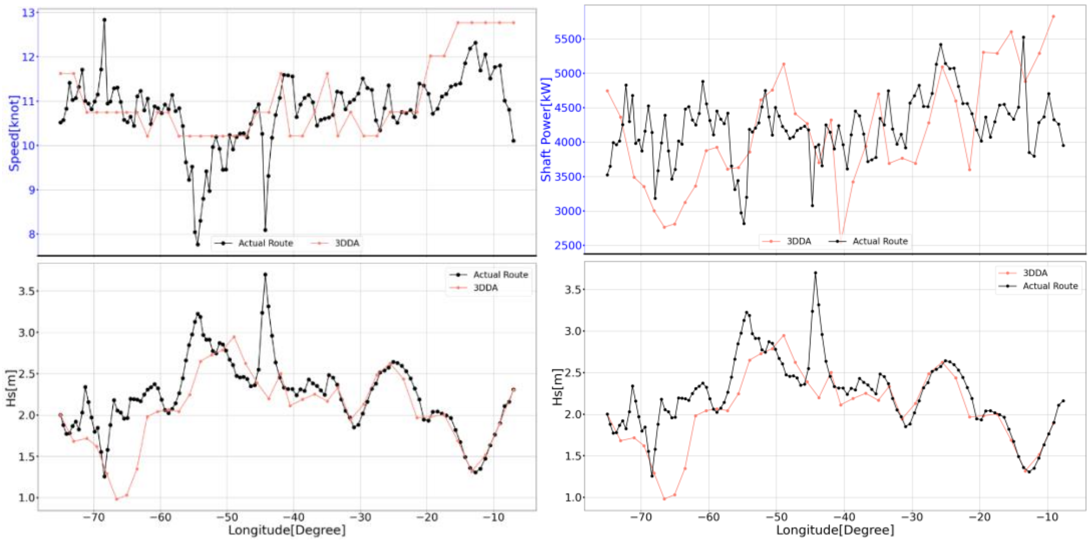


Figure 16: Speed, power and wave height comparison along the route

To better understand the source of these savings, Figure 16 (left) compares ship speed and wave height along the two routes. Around the 1/3 point of the voyage (near –50° to –40°W), the actual route encountered significant wave heights up to 3.54 meters, forcing the ship to reduce speed below 8 knots. In contrast, the optimized route faced lower waves (~2.5 meters) and maintained a more stable speed of about 10 knots. Because the optimized route avoids the storm zone, it operates under more favorable sea conditions, allowing smoother sailing.

Figure 16 (right) presents engine shaft power along the route. During the rough mid-Atlantic segment, the actual route's power output spikes above 4500 kW to counter wave resistance, while the 3DDA path remains below 4000 kW. In the later stages (east of –30°W), the optimized route gradually increases speed and power to meet the ETA, at times exceeding the actual route's power output. However, the early energy savings more than compensate for the added consumption during this acceleration phase. On average, the shaft power of the optimized route is over 10% lower than that of the actual route during the critical storm-affected portion.

In summary, Case 2 demonstrates the benefits of increased spatial and temporal resolution: the 3DDA algorithm is able to identify an alternative path that slightly deviates from the actual route, resulting in fuel savings of approximately 2% without delaying arrival. This case highlights the algorithm's ability to take advantage of its 3D optimization framework, adjusting both route and speed dynamically to avoid adverse conditions and operate in more fuel-efficient zones. It confirms the algorithm's practical value for long-distance voyage planning under real-world constraints.

Case 3 – Minimum voyage time path (stage = 120, no ETA constraint)

In this scenario, this chapter examines how the 3DDA algorithm behaves when fuel economy is disregarded and the goal is to minimize voyage time. By removing the ETA constraint, the algorithm is free to seek the fastest possible route, regardless of fuel consumption. The results show that the vessel could arrive approximately 50 hours earlier than planned, but at the cost of a substantial increase in fuel usage, as shown in Figure 17.

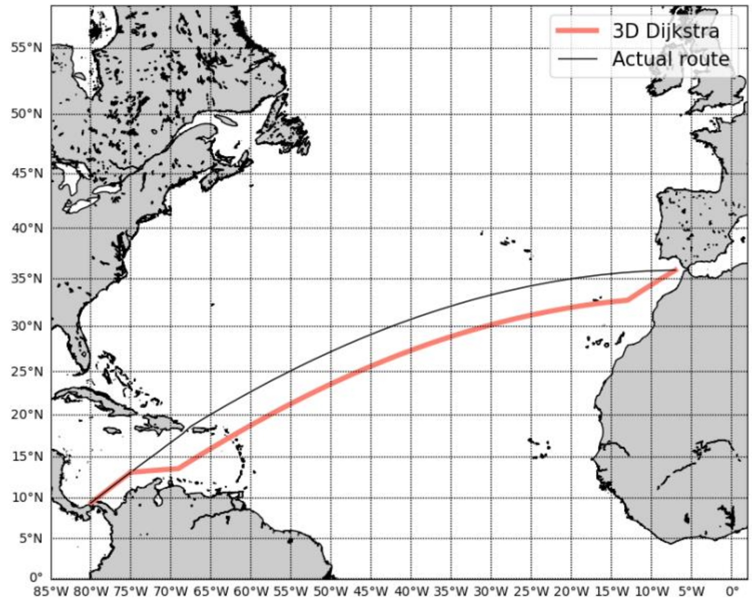


Figure 17: Route comparison in case 3 (the red line represents the 3DDA-optimized route, while the gray line shows the actual route).

As shown in Table 6, the 3DDA-generated fastest route has a total voyage time of approximately 347.3 hours (or 14.47 days), representing a 12.6% reduction from the original 397.5-hour plan. To achieve this, the vessel's average speed increases from around 12 knots (actual) to nearly 13.5 knots. However, the total fuel consumption rises sharply to about 475 tons, an increase of 92 tons (approximately +24%). The route length also slightly increases to 8014 km, about 1.8% longer than the actual path. This may be due to the algorithm selecting longer—but calmer—routes that support higher sustained speeds.

Table 6: Route performance comparison (Case 3).

	Distance [km]	ETA [h]	Fuel consumption [tons]
Actual route	7870	397.5	383
3DDA	8014	347.25	475

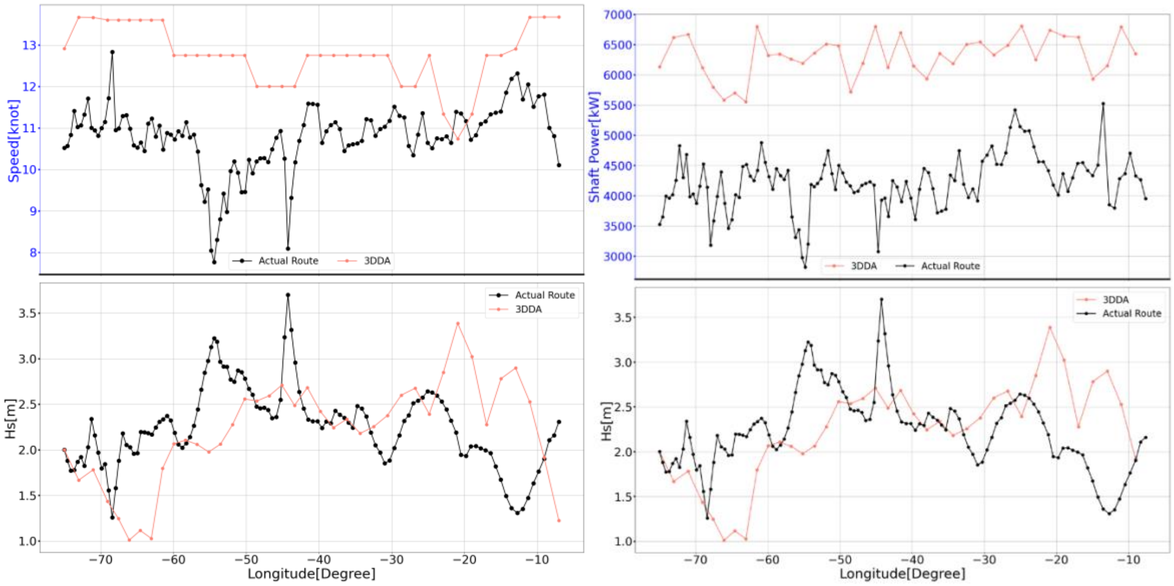


Figure 18: Speed, power and wave height comparison along the route (case 3).

As shown in Figure 18 (left), the optimized route maintains high speed throughout, with speeds exceeding 13 knots for most of the voyage and approaching 14 knots in the later stages. In contrast, the actual route slows to 9–10 knots in rougher sea conditions. The wave height profiles are similar, but around –20°E, the optimized route shows a brief deceleration corresponding to a wave height peak of 3.5 meters, after which speed resumes. As shown in Figure 18 (right), the red line (3DDA) indicates consistently high engine power, in the range of 5000–6000 kW, with peaks over 6500 kW in heavy seas—suggesting a power-through strategy. By contrast, the black line (actual) shows reductions in power during rough weather due to speed decreases. Overall, the fastest route adopts a clear trade-off strategy: higher fuel burn in exchange for reduced voyage time.

Further inspection of Figure 18 reveals that the optimized fast route is not a simple speed-up of the original track. In extreme wave regions (e.g., around –20°W), the 3DDA path even slows below the actual route's speed, indicating that the algorithm still applies local risk–cost assessments. It avoids full-speed sailing through peak storm zones when the trade-off becomes unfavorable. Nevertheless, its overall strategy is to maximize speed wherever possible, especially once conditions improve—immediately ramping up power to gain time. The final result shows that arriving 50 hours earlier comes at the cost of burning 24% more fuel. This highlights the critical trade-off between time and energy, a relationship the algorithm quantifies explicitly. Such insights are valuable in real-world operations: for instance, in scenarios involving high demurrage penalties or performance-based contract bonuses, the algorithm can guide decisions by showing exactly how much fuel must be sacrificed to save a specific amount of time. In this case, saving nearly 2 days of sailing time would require ~90 additional tons of fuel, nearly one-fourth of the baseline fuel budget.

Though uneconomical under normal conditions, Case 3 validates the algorithm's ability to explore time-optimal paths and generate corresponding cost curves. This capability can support data-driven decision-making for time-sensitive voyages, balancing economic, contractual, and operational objectives.

Case 4 – Minimum fuel consumption path (stage = 120, relaxed ETA)

In the final scenario, this chapter examines how much fuel can be saved if the vessel is allowed to extend its voyage duration modestly, operating at lower speeds within safe operational limits. The ETA is relaxed by approximately 18.75 hours (about 4.7%, or 0.78 days). Under this setting, the 3DDA algorithm generates an ultra fuel-efficient route, consuming only 347 tons of fuel—a reduction of 36 tons compared to the actual voyage, achieving a 9.4% fuel saving, equivalent to nearly one-tenth of the total fuel consumption.

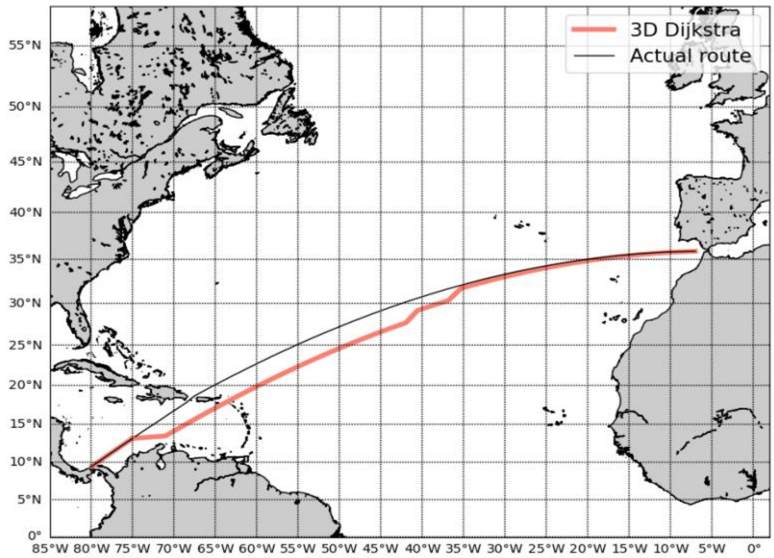


Figure 19: Route comparison in case 4 (the red line represents the 3DDA-optimized route, while the gray line shows the actual route).

The optimized route covers 7968 km, which is 98 km longer than the actual voyage (+1.2%), and the total sailing time extends to 416.25 hours (17 days and 8.25 hours). Although the route is slightly longer and the arrival is delayed, the significant reduction in fuel consumption demonstrates the algorithm's ability to select calmer sea regions and operate at lower average speeds. As shown in Figure 19, the energy-saving path maintains a consistent cruising speed below 10 knots across most of the Atlantic segment, avoiding almost all high-wave areas. In contrast, the actual route increases speed in some segments to meet schedule and passes through rougher waters. The wave height comparison reveals that the optimized path avoids major wave peaks, keeping significant wave height around 2 meters, while the actual route encounters peaks exceeding 3 meters between –50°W and –40°W.

Table 7: Route performance comparison (Case 4).

	Distance [km]	ETA [h]	Fuel consumption [tons]
Actual route	7870	397.5	383
3DDA	7968	416.25	347

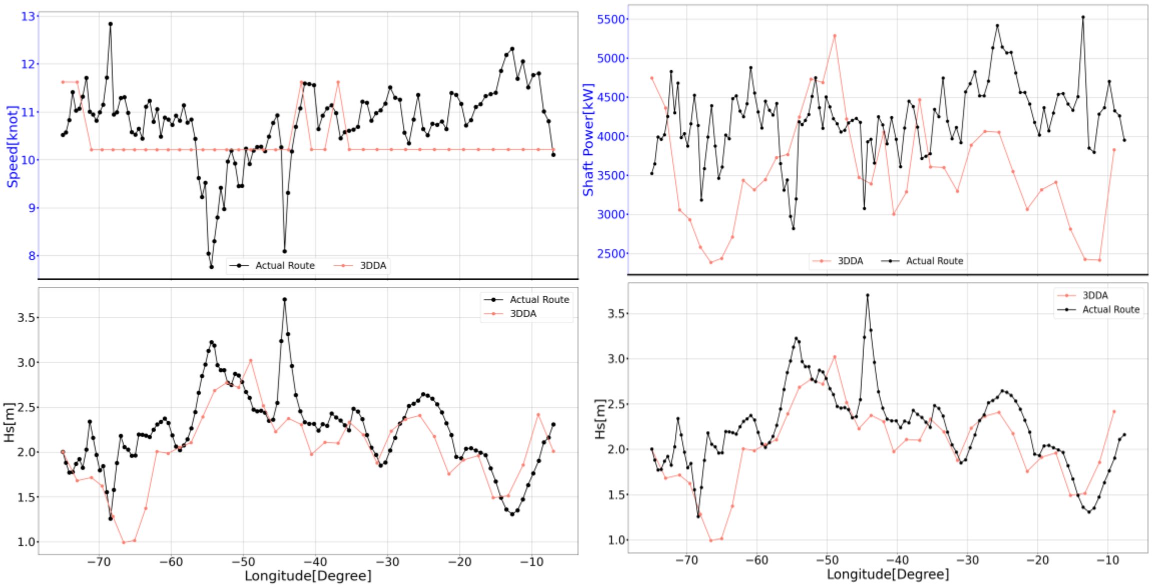


Figure 20: Speed, power and wave height comparison along the route (case 4).

As shown in Figure 20 (left), The red line (optimized) shows consistently low and stable speeds, mostly under 10 knots, with minimal fluctuations. The black line (actual) accelerates to 11–12 knots in later segments. Below, the wave height profile confirms that the optimized route successfully avoids wave peaks over 3.5 meters, staying closer to 2.8 meters. As shown in Figure 20 (right), the engine power curve (red) for the fuel-efficient route remains smooth and low, averaging around 3500 kW, while the actual route (black) maintains an average above 4200 kW with frequent spikes. This indicates that the optimized path keeps the main engine operating at lower, more stable loads—significantly reducing fuel consumption.

The strategy in this scenario is clear: slow down and avoid high seas, thereby reducing required engine output and saving fuel. By allowing a half-day delay, the vessel is able to operate at lower speeds and power, and strategically reroute to bypass unfavorable weather.

Case 4 demonstrates that moderately extending voyage time can lead to substantial fuel savings—up to 9.4% in this case. For shipping companies, this finding is highly relevant: on non-urgent voyages, slower steaming is an effective strategy for energy conservation. The 3DDA algorithm provides a quantitative solution for the time-versus-fuel trade-off, allowing decision-makers to balance cost and operational objectives. Based on the 9.4% fuel savings versus 4.7% additional time, a fuel/time trade-off curve can be derived to support optimal speed planning and operational scheduling.

Overall analysis of the 4 cases

The results from the four experimental scenarios comprehensively demonstrate the capabilities and effectiveness of the 3D weather routing algorithm:

1) In Case 1, under conditions closely matching the actual voyage, the algorithm successfully reproduced the traditional route with slight improvements, confirming its reliability and correctness.

2) In Case 2, with enhanced discretization but the same ETA, the algorithm achieved a 10 tons reduction in fuel consumption, showcasing its potential for fuel-efficient optimization even under strict scheduling.

3) Cases 3 and 4, where ETA constraints were removed, represent extreme scenarios—one focused on minimum voyage time, the other on minimum fuel use. The algorithm provided quantitative insights into the trade-off between fuel and time: the fastest route significantly increased fuel consumption, while the slowest route achieved notable fuel savings. These results, difficult to estimate based on experience alone, are made clear through algorithmic modeling.

Table 4 - Table 7 summarize the key metrics of each case and illustrates the fuel–time trade-off.

- Comparing Case 2 to Case 4, extending the voyage by 18.5 hours led to 28 tons of fuel savings—approximately 1.5 tons per hour delayed.
- In contrast, Case 3 versus Case 2 shows that arriving 50 hours earlier consumed 100 additional tons of fuel, equating to 2 tons per hour saved.

This non-linear trade-off provides valuable guidance for selecting optimal voyage strategies. Generally, under current fuel price and demurrage cost conditions, aggressively accelerating to arrive early is rarely economical, whereas slight delays and reduced speeds offer a cost-effective solution.

The method developed enables such analysis to be performed scientifically and quantitatively, supporting data-driven operational decision-making for green and intelligent ship routing.

Annex III – User Manual for NTUA Weather Routing Tool

Introduction

This is the User's Manual for the installation and use of the NTUA Weather Routing Tool.

The tool provides a practical solution for route planning under realistic weather conditions, improving operational efficiency and energy savings. It is a MATLAB-based application (also available as a standalone executable) developed to optimize a vessel's voyage with respect to Fuel Oil Consumption (FOC), while accounting for prevailing weather conditions. Moreover MATLAB's core functions along with the Genetic Algorithm implementation available in the Optimization Toolbox are used.

A key feature of the tool is the development of a digital twin of the vessel under investigation, and all necessary calculations considering its unique characteristics rather than being generic. An optimal path between two given points (ports) that minimizes FOC over a certain period of time is to be determined. For that period of time, the prevailing weather conditions are sourced from Copernicus Marine Service and include data regarding waves, wind and ocean currents. Along any potential route, the vessel speed is assumed to be constant and is defined by the user. As far as ocean currents are concerned, they impact the required engine power along the transit to maintain that target speed.

The optimization process evaluates multiple candidate routes using genetic algorithm (GA), iteratively improving towards the best solution. The algorithm can explore feasible solutions under operational limits and criteria that can also be implemented such as duration/depth limitations, etc. More details are provided in D3.2 [5].

Demonstration case

For the demonstration of the Weather Routing Tool, a demo has been created including only a past voyage of the KASTOR vessel. The original voyage started on 11.12.2024 at 00:00 from port of Panama and was intended for the port of Mersin. However, for the purposes of this demo and route optimization, only the cross-Atlantic segment of the journey is considered. Therefore, the destination has been limited to a point near east of Gibraltar. The selection to analyze this part of the voyage was based on the fact that the potential fuel savings of the part of the voyage in the Mediterranean would be much less compared to the corresponding one in the Atlantic Ocean, due to the weather conditions encountered in the two regions. Therefore, performing optimization in the Mediterranean Sea, where significant deviations would not be likely to occur, and thus fuel saving potential would be minor compared with the Atlantic passage, while the computational cost would also increase.

Route optimization is performed using a genetic algorithm with 100 individuals per generation and a total of 10 generations. A limitation is also set to the algorithm, that terminates earlier the optimization process, if no significant improvement is observed between two subsequent generations. In the presented setup of the demo with the maximum 1000 candidate routes for evaluation, the tool is able to reach a satisfactory solution within a reasonable timeframe.

In the following, the installation of the tool as well as the graphical user interface (GUI) are introduced in detail, highlighting also the configurable parameters available to the user.

Installation

To install the NTUA Weather Routing Tool, the following steps must be completed:

The installation package folder is named "Weather_Routing_NTUA"

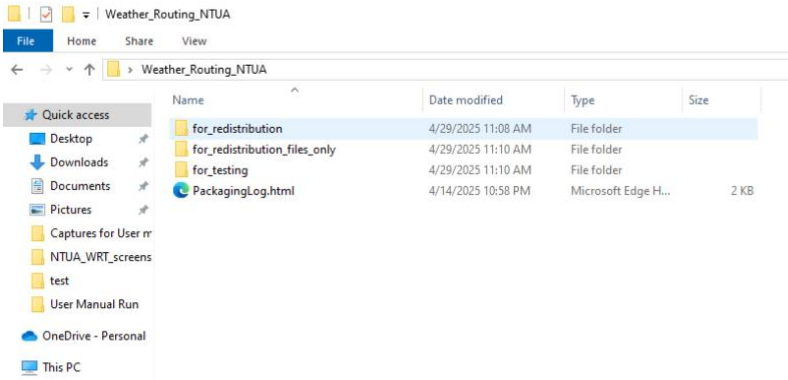


Figure 21: Installation Package

- Open the folder named "for_redistribution"
- Unzip the file named "MyAppInstaller_mcr.zip"

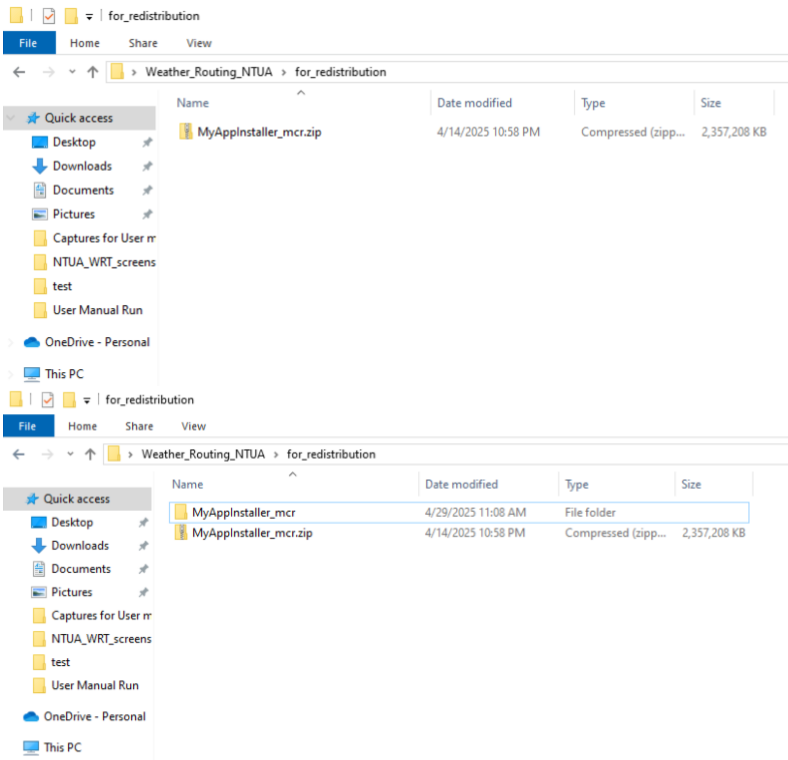


Figure 22: Snapshot of folder before (top) and after (bottom) unzipping the MyAppInstaller_mcr.zip file

Run “MyAppInstaller_mcr.exe” to begin installation

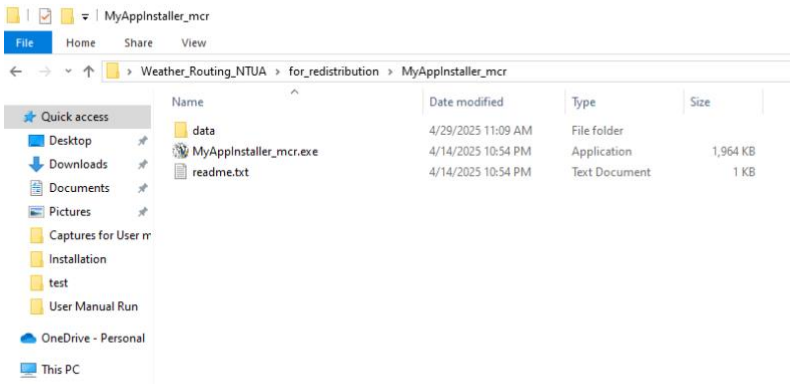
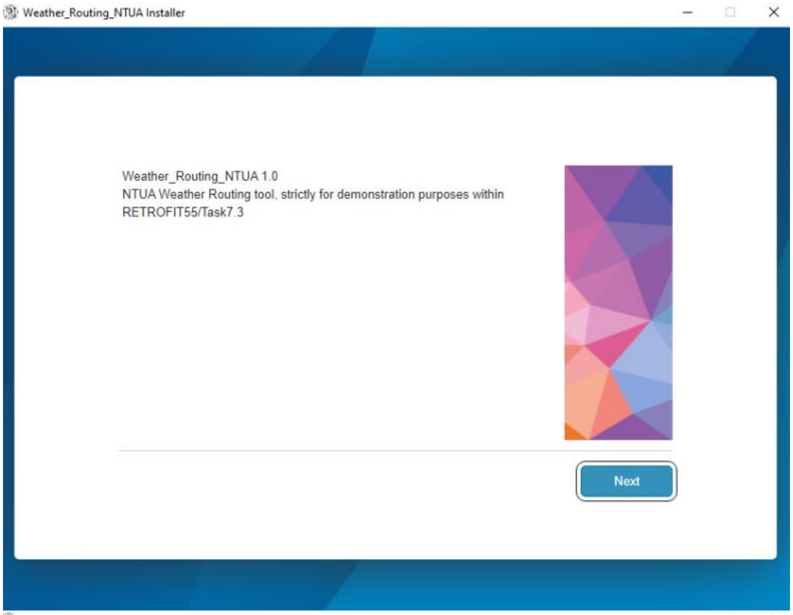
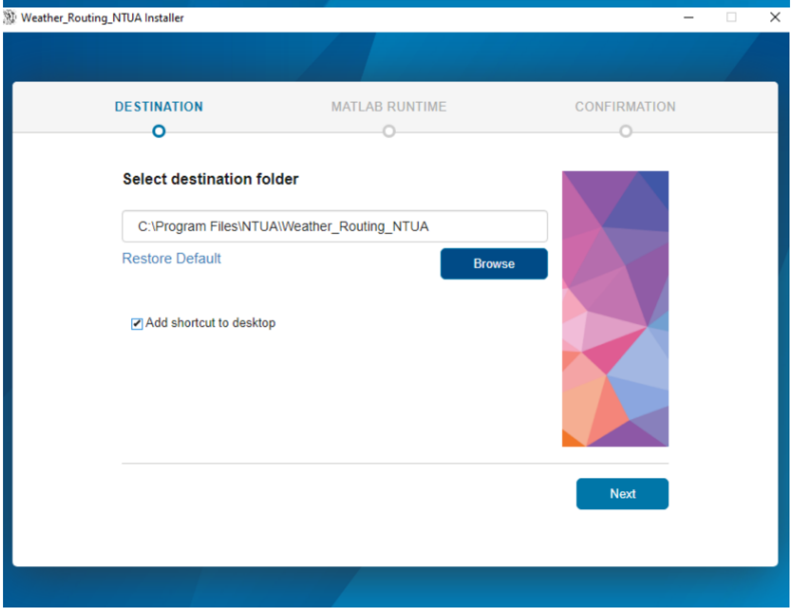
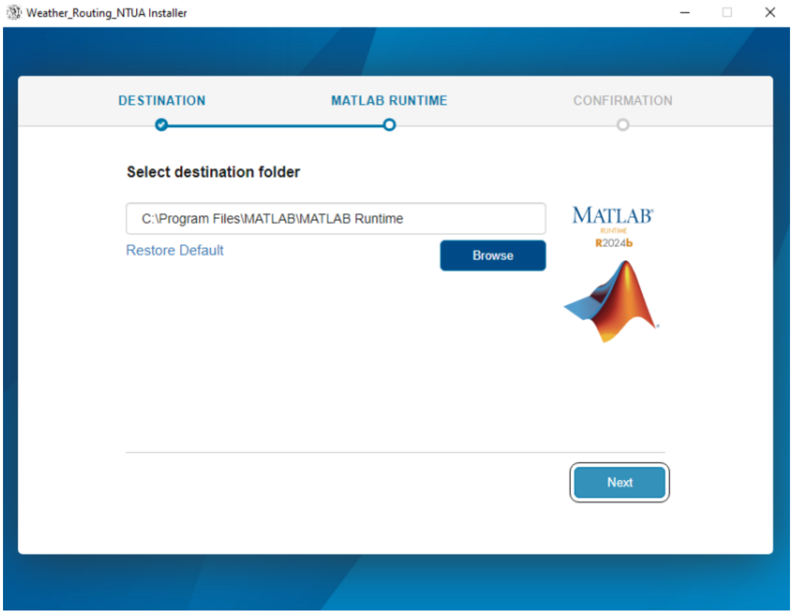


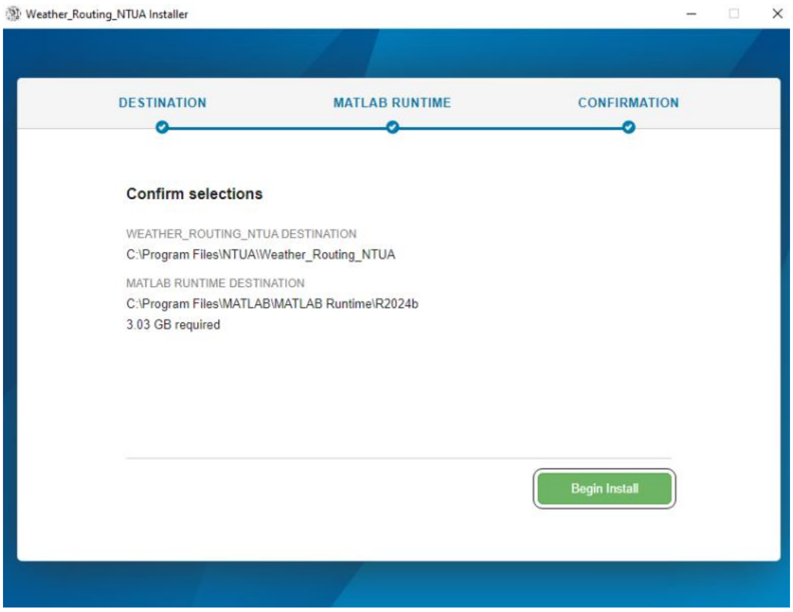
Figure 23: Snapshot of “MyAppInstaller_mcr” folder

- Follow the installation instructions
- Select the option "Add shortcut to desktop"
- Install the MATLAB Runtime, after reviewing the license agreement
- Press the "Begin Install" button to proceed with the installation
- Wait for the installation to complete
- Press the "Close" button after the installation is completed






Weather_Routing_NTUA Installer
DESTINATION
MATLAB RUNTIME
CONFIRMATION
Select destination folder
C:\Program Files\MATLAB\MATLAB Runtime
Restore Default
Browse
MATLAB
R2024b
Next


Weather_Routing_NTUA Installer
DESTINATION
MATLAB RUNTIME
CONFIRMATION
Confirm selections
WEATHER_ROUTING_NTUA DESTINATION
C:\Program Files\NTUA\Weather_Routing_NTUA
MATLAB RUNTIME DESTINATION
C:\Program Files\MATLAB\MATLAB Runtime\R2024b
3.03 GB required
Begin Install

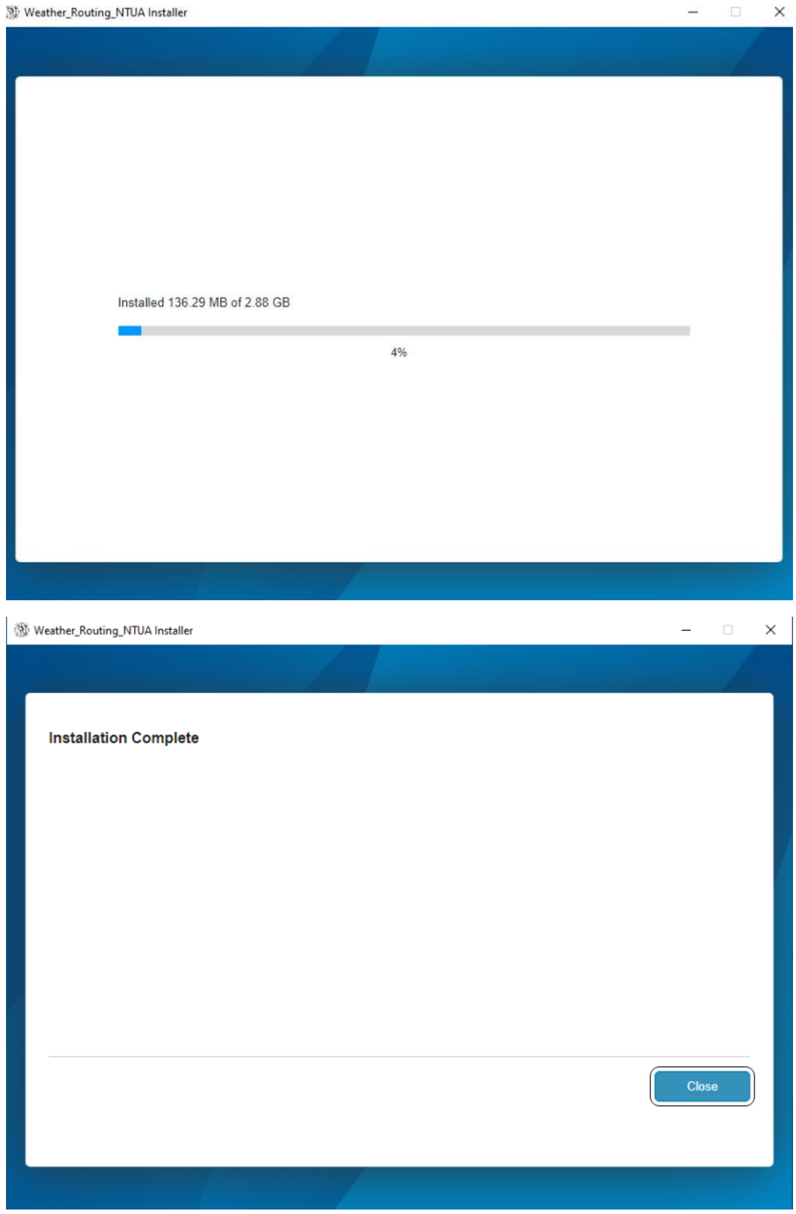


Figure 24: Snapshot of installations step

The contents of the program folder and the default installation path are shown in the snapshot

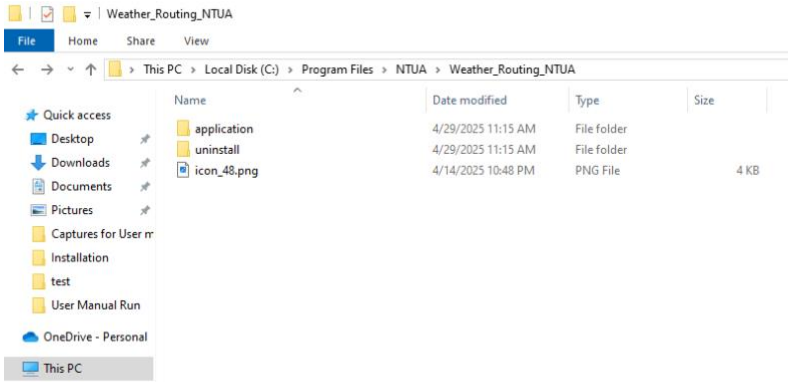


Figure 25: Snapshot of program folder

<u>Run Folder</u>

To perform weather routing optimization, a new folder (hereafter referenced as “Run folder”) needs to be created, and the following files must be copied inside:

1. Weather_Routing_NTUA shortcut to the executable
2. NTUALogo.jpg
3. RetrofitLogo.jpg

Double clicking the shortcut activates the executable and a Graphical User Interface Window will open. The user can interactively enter the required data to perform the weather routing optimization.

The Run folder with the necessary files to perform calculations is shown in Figure 26.

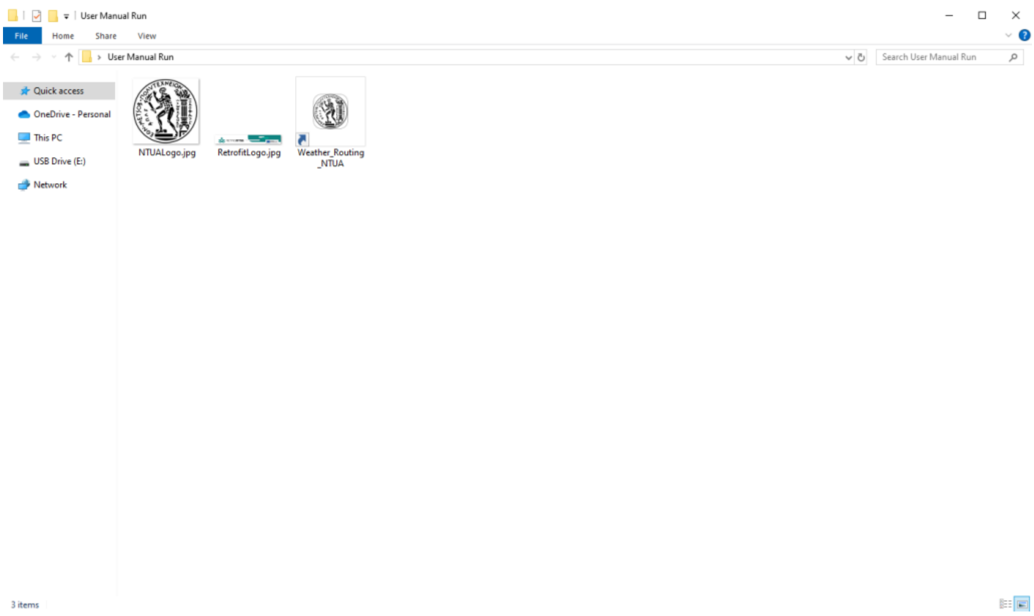


Figure 26: Run folder with the initial necessary files

Graphical User Interface (GUI) Window Description

In this chapter, explanatory notes regarding the Graphical User Interface for the Weather Routing Tool is presented.

The available input variables and notes relevant to the demonstration case are listed in Table 8.

Table 8: Input variables description

Input Variable	Description	Notes
Vessel Name	Name of vessel	Fixed to “MV KASTOR”
Vessel Speed	Vessel speed in knots	Range 10-15 kn for which calm water resistance data are available
Mean Draft	Vessel’s mean draft	Fixed at 12 m according to ship’s mean draft for the specific voyage
Port of Departure	Port of departure	Fixed to “Panama” for demonstration purposes
Port of Arrival	Port of Arrival	Fixed to “Mersin” for demonstration purposes. However, route optimization is performed exclusively over the cross-Atlantic passage part of the voyage
Departure Date	Departure date	Fixed on “11/12/2024 00:00”, corresponding to the departure date of the examined historical voyage
ETA	Estimated Time of Arrival	Estimated time of arrival based on ship’s speed and orthodrome route distance
Voyage Duration	Orthodrome voyage duration	Estimated voyage duration, based on ship’s speed and the orthodrome route distance
Delay Tol	Delay tolerance in hours	Time delay allowed, compared to the orthodrome voyage duration. If any examined route leads to an exceedance of the orthodrome voyage duration, increased by the delay tolerance, it is considered infeasible route. In general, the increase of the delay tolerance relaxes the optimization process, allowing for the exploration of more efficient routes, at the penalty of a later arrival.

The input parameters are:

1. Vessel Name – Locked in demonstration purposes
2. Vessel Speed – Editable field, to input vessel speed in knots.
3. Mean Draft – Editable field, to input vessel's draft in meters (but fixed within the code).
4. Port of Departure – Selection of departure port from a list. For demonstration purposes only "Panama" can be selected
5. Port of Arrival – Selection of arrival port from a list. For demonstration purposes only "Mersin" can be selected
6. Departure Date – Locked for demonstration purposes, corresponding to the departure date of the voyage

➢ Press the ETA button to estimate the arrival date based on input vessel speed and orthodrome distance.

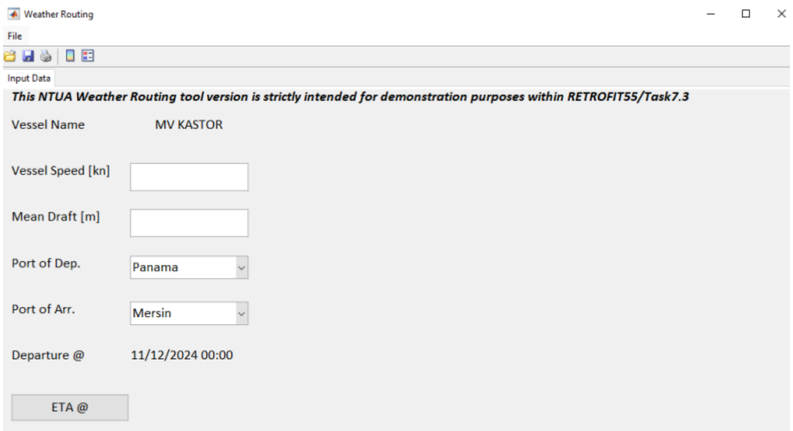


Figure 27: Initial stage of input parameters in the GUI window

The input parameters are:

7. Voyage Duration – Locked field displaying the voyage duration based on the orthodrome distance
8. Delay tolerance – Editable field, to input an allowable time tolerance in hours.

➢ Press the Apply button to finalize input data entry

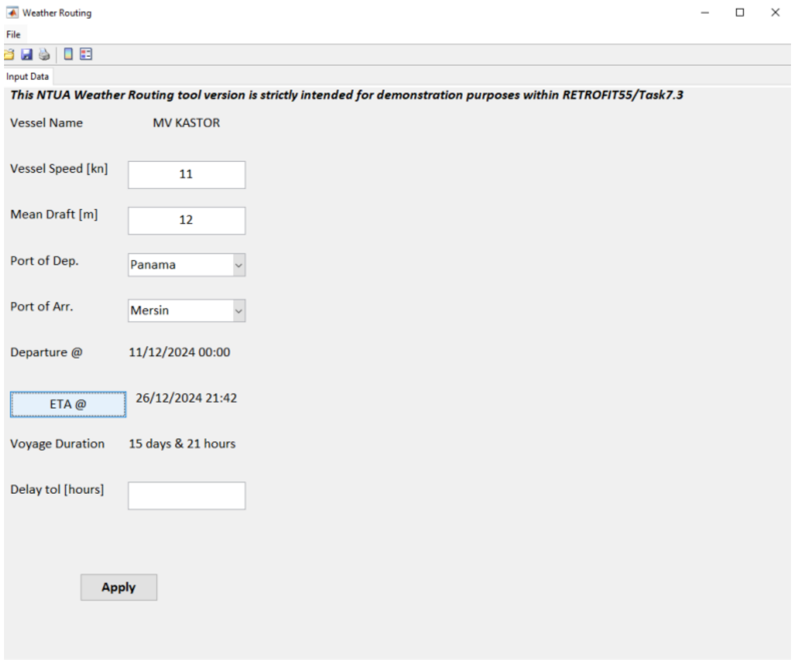


Figure 28: Final stage of input parameters in the GUI window

After pressing the Apply button, a map is plotted at the right-hand side of the window

➢ Press the Start button to begin the weather routing optimization calculation

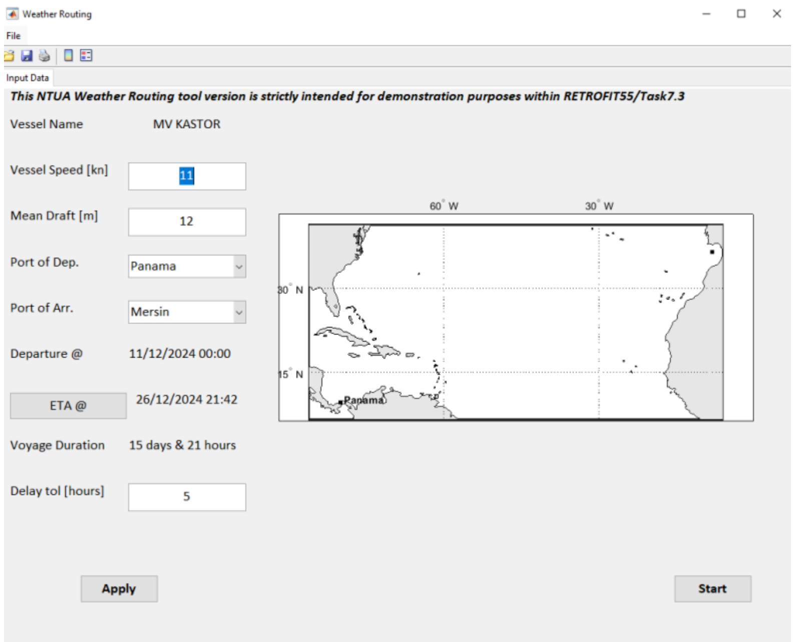


Figure 29: Complete input tab in the GUI window

After completing the weather routing optimization, two new tabs appear in the GUI window

1. The “Output Data” tab containing data regarding the optimal and orthodrome route and the relative differences between the two.
2. The “Optimal Route” tab containing projected daily data for the optimal route.

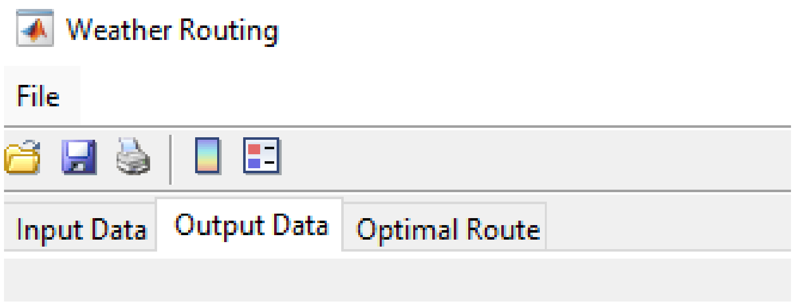
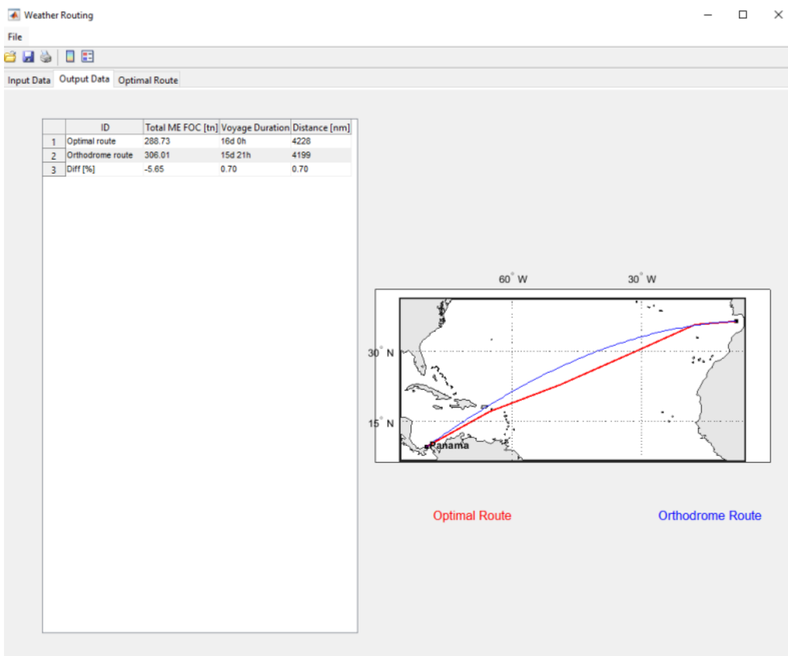


Figure 30: Generated Output Tabs

The “Output Data” tab contains:

1. A table with data containing the Total Main Engine Fuel Oil Consumption, the voyage duration and the distance of the route. The results refer to the optimal route, the orthodrome route and the percentage difference of the two routes for each quantity. In the case that an optimal route cannot be found, only the orthodrome route results are given in the table.
2. A map figure depicting the orthodrome route (in blue) and the optimal route (in red).

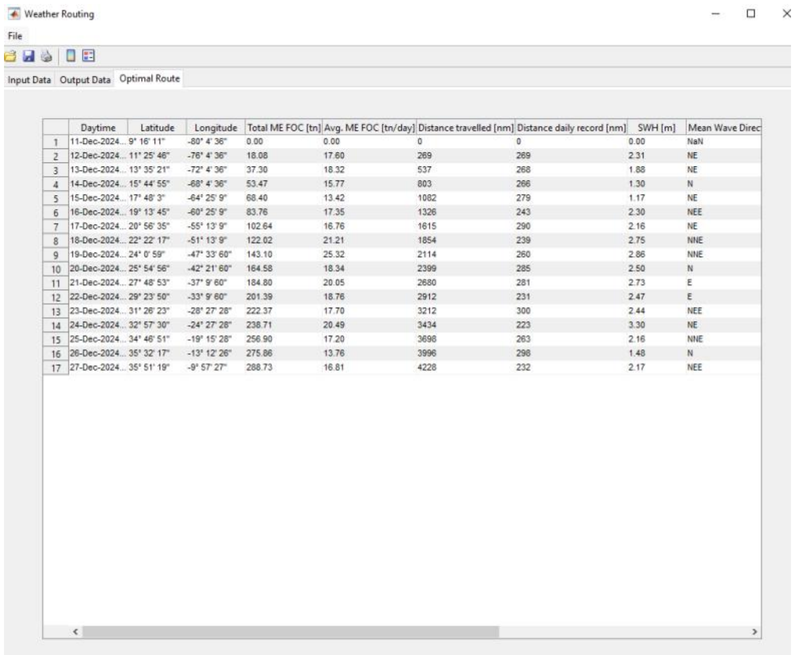


	ID	Total ME FOC [tn]	Voyage Duration	Distance [nm]
1	Optimal route	288.73	16d 0h	4228
2	Orthodrome route	306.01	15d 21h	4199
3	Diff [%]	-5.65	0.70	0.70

Figure 31: Output Data Tab

The "Optimal Route" tab contains daily information for the optimal route for the following quantities:

1. Daytime: Date and Time corresponding to approximately 24h interval (checkpoint[1])
2. Latitude & Longidute: Positional coordinates of the checkpoint
3. Total ME FOC: Total Main Engine fuel oil consumption (FOC) until the specific checkpoint
4. Avg. ME FOC: Average daily Main Engine FOC
5. Distance travelled: Distance travelled until the specific checkpoint
6. Distance daily record: Distance covered between successive checkpoints
7. SWH: Significant Wave Height (including wind waves and swell) at the checkpoint
8. Mean Wave Direction: Mean wave direction at the checkpoint
9. TWS: True Wind Speed at the checkpoint
10. TWD: True Wind Direction at the checkpoint
11. Ocean Current Speed: Ocean current speed at the checkpoint
12. Mean Ocean Current Direction: Mean ocean current direction at the checkpoint



	Daytime	Latitude	Longitude	Total ME FOC [tn]	Avg. ME FOC [tn/day]	Distance travelled [nm]	Distance daily record [nm]	SWH [m]	Mean Wave Direc
1	11-Dec-2024...	9° 16' 11"	-80° 4' 36"	0.00	0.00	0	0	0.00	NaN
2	12-Dec-2024...	11° 25' 46"	-76° 4' 36"	18.08	17.60	269	269	2.31	NE
3	13-Dec-2024...	13° 35' 21"	-72° 4' 36"	37.30	18.32	537	268	1.88	NE
4	14-Dec-2024...	15° 44' 55"	-68° 4' 36"	53.47	15.77	803	266	1.30	N
5	15-Dec-2024...	17° 48' 3"	-64° 25' 9"	68.40	13.42	1082	279	1.17	NE
6	16-Dec-2024...	19° 13' 45"	-60° 25' 9"	83.76	17.35	1326	243	2.30	NEE
7	17-Dec-2024...	20° 56' 35"	-55° 13' 9"	102.64	16.76	1615	290	2.16	NE
8	18-Dec-2024...	22° 22' 17"	-51° 13' 9"	122.02	21.21	1854	239	2.75	NNE
9	19-Dec-2024...	24° 0' 59"	-47° 33' 60"	143.10	25.32	2114	260	2.86	NNE
10	20-Dec-2024...	25° 54' 56"	-42° 21' 60"	164.58	18.34	2399	285	2.50	N
11	21-Dec-2024...	27° 48' 53"	-37° 9' 60"	184.80	20.05	2680	281	2.73	E
12	22-Dec-2024...	29° 23' 50"	-33° 9' 60"	201.39	18.76	2912	231	2.47	E
13	23-Dec-2024...	31° 26' 23"	-28° 27' 28"	222.37	17.70	3212	300	2.44	NEE
14	24-Dec-2024...	32° 57' 30"	-24° 27' 28"	238.71	20.49	3434	223	3.30	NE
15	25-Dec-2024...	34° 46' 51"	-19° 15' 28"	256.90	17.20	3698	263	2.16	NNE
16	26-Dec-2024...	35° 32' 17"	-13° 12' 26"	275.86	13.76	3996	298	1.48	N
17	27-Dec-2024...	35° 51' 19"	-9° 57' 27"	288.73	16.81	4228	232	2.17	NEE

Figure 32: Optimal Route Tab

[1] Checkpoint: The closest available grid point to the vessel's position every 24 hours along the optimized path.

Output Files

The output files are generated in Run folder and contain:

1. A HTML report named “NTUA Weather Routing Report” with the relevant weather routing optimization data.
2. Image files of a map where prevailing weather data and the ship’s position are illustrated. One jpg-image file is generated for every day (Day##) of the optimal route voyage.

In Figure 33 a screenshot of the Run folder, after completing the weather routing optimization calculation, is given.

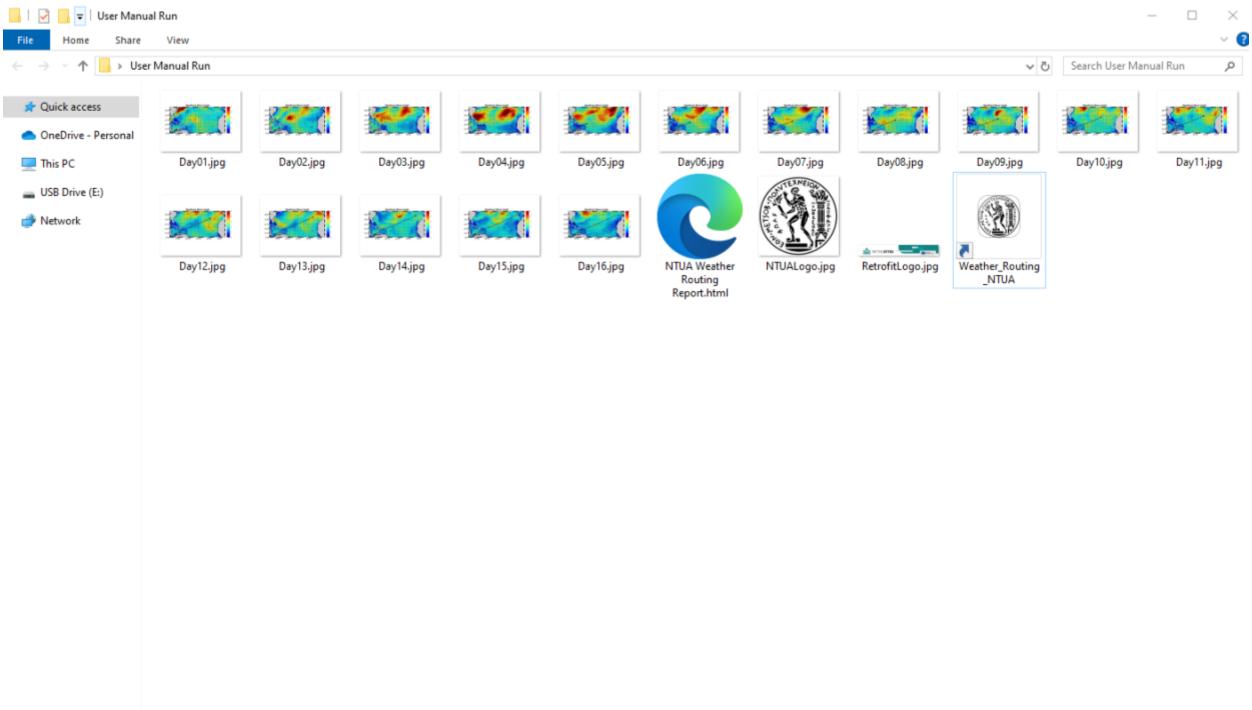


Figure 33: Run folder screenshot after calculation completion

Weather Routing Optimization Report

The results obtained after the completion of the route optimization are summarized in an automatically generated HTML report. The report can be opened using any browser.

The report begins with the illustration of RETROFIT55 and NTUA logos along with a disclaimer note. A text paragraph containing important information of the voyage under examination regarding the vessel loading condition and speed, as well as port and date of departure and arrival port follows next. Subsequently, a table containing comparative results between the orthodrome and optimal route is given, as discussed in the “GUI Output Data Tab” (Figure 31). Explanatory notes and a table containing daily data for the optimal route, as discussed in the “GUI Optimal Route Tab” (Figure 32) follow next. Finally, map figures containing the position of the ship and the prevailing weather conditions (significant wave height and mean wave direction have been selected) in the region per day, are arranged and shown in tabular form. In Figure 34 and Figure 35, screenshots of the automatically generated report are given.

RETROFIT55

Funded by the European Union

This is a Report generated by NTUA Weather Routing tool, strictly for demonstration purposes within RETROFIT55/Task7.3

Weather Routing Report for MV KASTOR

Mean Draft= 12.00 [m] - Vessel Speed= 11.00 [kn]

Voyage from Panama to Mersin (Optimized part only for trans-Atlantic crossing). Started at: 11/12/2024 00:00

Optimal Route comparison against Orthodrome

Weather Optimized Route

ID	Total ME FOC [tn]	Voyage Duration	Distance [nm]
Optimal route	288.73	16d 0h	4228
Orthodrome route	306.01	15d 21h	4199
Diff [%]	-5.65	0.70	0.70

Daily Results for the Optimal Route

ME FOC: Main Engine Fuel Oil Consumption

SWH: Significant Wave Height (incl. wind waves and swell)

TWS: True Wind Speed

TWD: True Wind Direction

Optimal Route Voyage Data

Daytime	Latitude	Longitude	Total ME FOC [tn]	Avg. ME FOC [tn/day]	Distance travelled [nm]	Distance daily record [nm]	SWH [m]	Mean Wave Direction From	TWS [m/s]	TWD	Ocean Current Speed [kn]	Mean Ocean Current Direction To
11-Dec-2024 00:00:00	9° 16' 11"	-80° 4' 36"	0.00	0.00	0	0	0.00	NaN	0.00	NaN	0.00	NaN
12-Dec-2024 00:30:03	11° 25' 46"	-76° 4' 36"	18.08	17.60	269	269	2.31	NE	12.14	NNE	0.47	W
13-Dec-2024 00:51:32	13° 35' 21"	-72° 4' 36"	37.30	18.32	537	268	1.88	NE	9.79	NE	0.84	W

Figure 34: Generated report output – Initial Part

23-Dec-2024 03:59:43	31° 26' 23"	-28° 27' 28"	222.37	17.70	3212	300	2.44	NEE	10.53	NE	0.26	SWW
24-Dec-2024 00:14:46	32° 57' 30"	-24° 27' 28"	238.71	20.49	3434	223	3.30	NE	11.11	NE	0.15	NEE
25-Dec-2024 00:10:03	34° 46' 51"	-19° 15' 28"	256.90	17.20	3698	263	2.16	NNE	5.73	SEE	0.15	N
26-Dec-2024 03:16:03	35° 32' 17"	-13° 12' 26"	275.86	13.76	3996	298	1.48	N	7.13	NE	0.34	SEE
27-Dec-2024 00:23:50	35° 51' 19"	-9° 57' 27"	288.73	16.81	4228	232	2.17	NEE	8.21	E	0.27	SW

Route Plan

12-Dec-2024 00:30:03 @ (11° 25' 46" , -76° 4' 36")	13-Dec-2024 00:51:32 @ (13° 35' 21" , -72° 4' 36")	14-Dec-2024 01:02:53 @ (15° 44' 55" , -68° 4' 36")

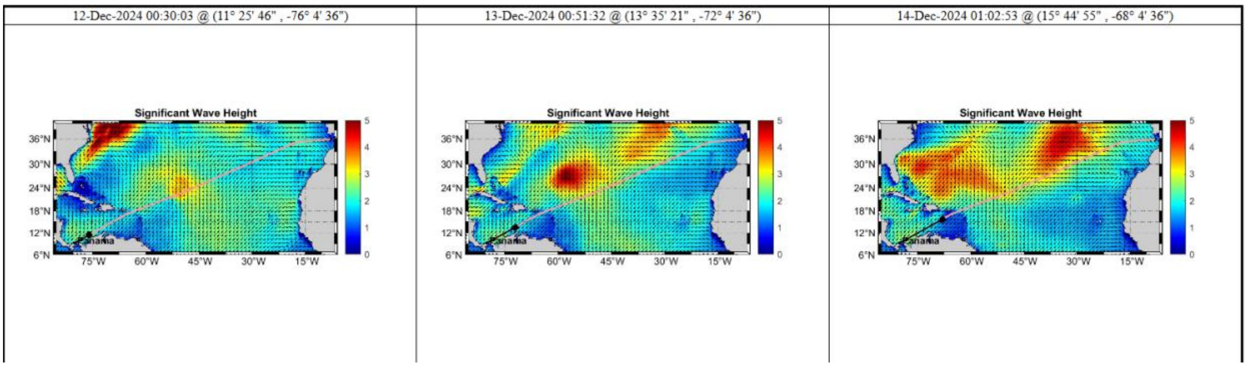


Figure 35: Generated report output – Route Plan

Route Plan Daily Map Plots

In this section, the generated map plot image files are described. In Figure 36 a typical daily map plot image is shown. The black dot marker represents the position of the ship on the map, at the current checkpoint. The line connecting the departure and arrival positions represents the optimal route. The part of the route that is already covered by the ship, until the checkpoint, is displayed in black colour, while the remaining part of the route is depicted in pink colour. On top of the optimal route, a colour map corresponding to the significant wave height, including wind waves and swell, is also displayed. The legend at the right-hand side of the map represents the values of the significant wave height in meters. Finally, the black arrows in the map, represent the mean wave direction.

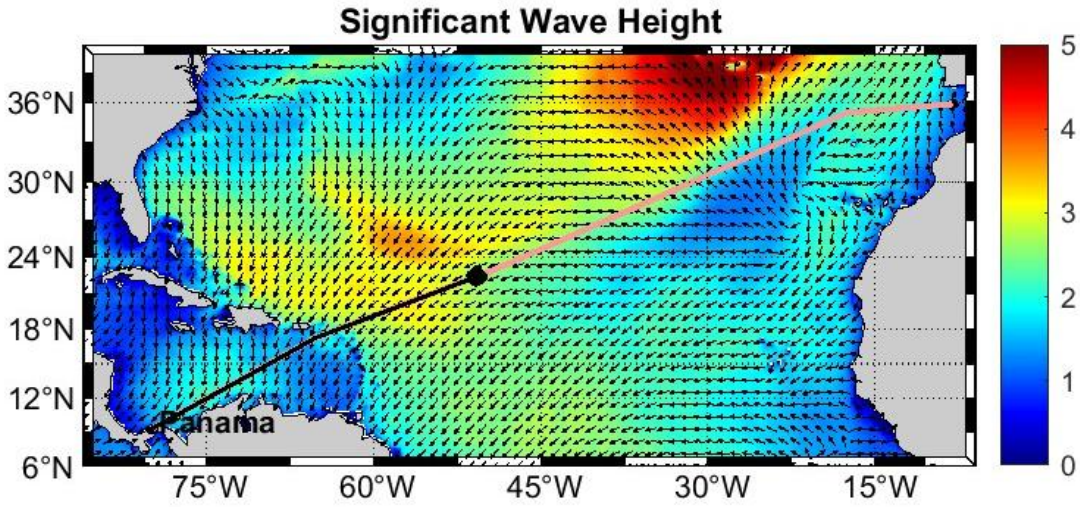


Figure 36: Map Plot

Annex IV – Sample report generated by NTUA Weather Routing Tool

RETROFIT55
Funded by the European Union

This is a Report generated by NTUA Weather Routing tool, strictly for demonstration purposes within RETROFIT55/Task7.3

Weather Routing Report for MV KASTOR

Mean Draft= 12.00 [m] - Vessel Speed= 11.00 [kn]

Voyage from Panama to Mersin (Optimized part only for trans-Atlantic crossing). Started at: 11/12/2024 00:00

Optimal Route comparison against Orthodrome

Weather Optimized Route

ID	Total ME FOC [tn]	Voyage Duration	Distance [nm]
Optimal route	288.73	16d 0h	4228
Orthodrome route	306.01	15d 21h	4199
Diff [%]	-5.65	0.70	0.70

Daily Results for the Optimal Route

ME FOC: Main Engine Fuel Oil Consumption

SWH: Significant Wave Height (incl. wind waves and swell)

TWS: True Wind Speed

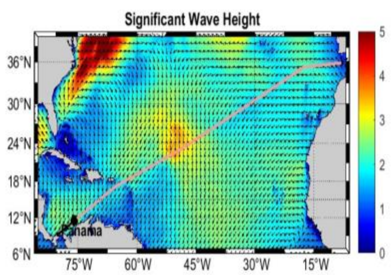
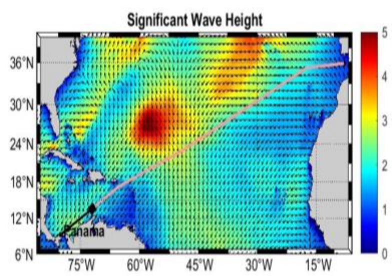
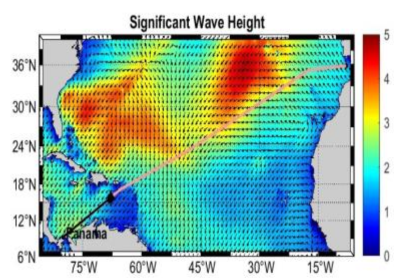
TWD: True Wind Direction

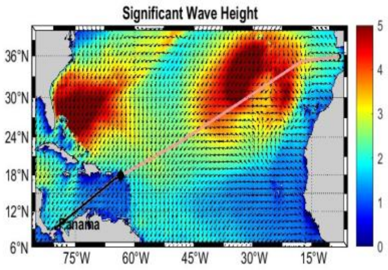
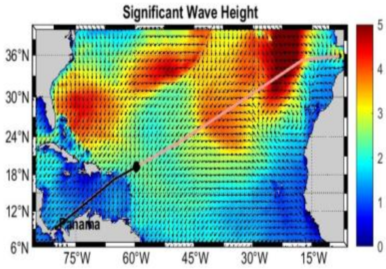
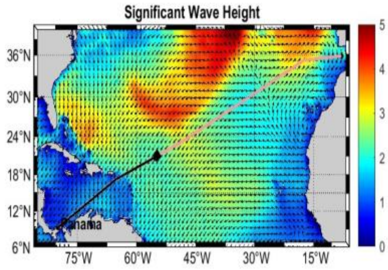
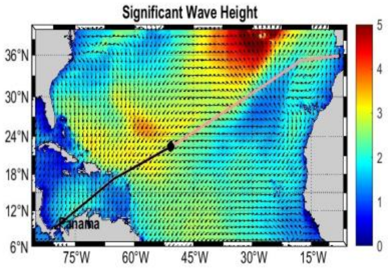
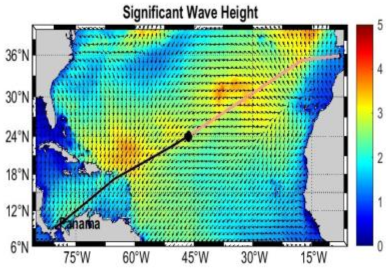
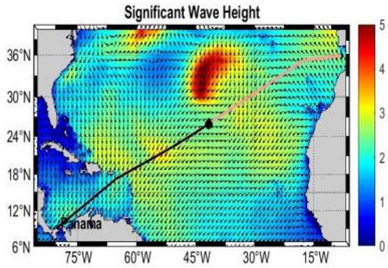
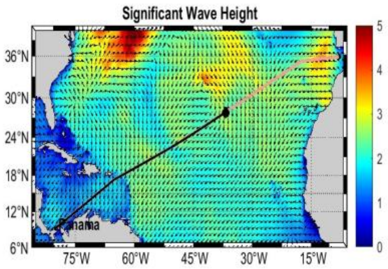
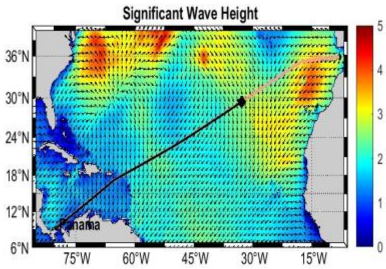
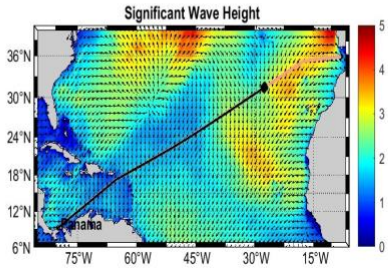
Optimal Route Voyage Data

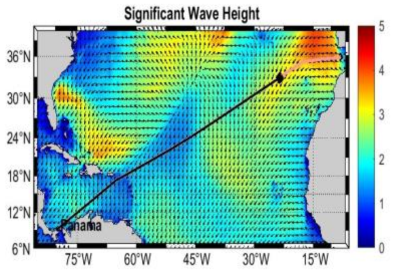
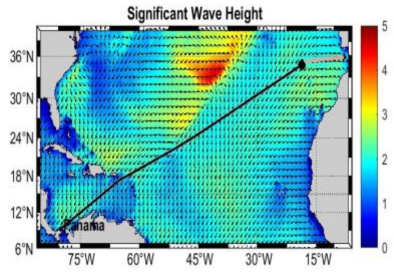
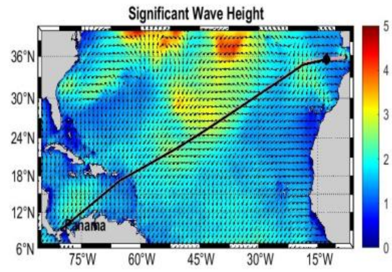
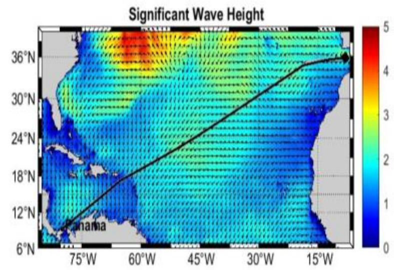
Daytime	Latitude	Longitude	Total ME FOC [tn]	Avg. ME FOC [tn/day]	Distance travelled [nm]	Distance daily record [nm]	SWH [m]	Mean Wave Direction From	TWS [m/s]	TWD	Ocean Current Speed [kn]	Mean Ocean Current Direction To
11-Dec-2024 00:00:00	9° 16' 11"	-80° 4' 36"	0.00	0.00	0	0	0.00	NaN	0.00	NaN	0.00	NaN
12-Dec-2024 00:30:03	11° 25' 46"	-76° 4' 36"	18.08	17.60	269	269	2.31	NE	12.14	NNE	0.47	W
13-Dec-2024 00:51:32	13° 35' 21"	-72° 4' 36"	37.30	18.32	537	268	1.88	NE	9.79	NE	0.84	W
14-Dec-2024 01:02:53	15° 44' 55"	-68° 4' 36"	53.47	15.77	803	266	1.30	N	7.27	NNE	0.38	SW
15-Dec-2024 02:24:53	17° 48' 3"	-64° 25' 9"	68.40	13.42	1082	279	1.17	NE	3.88	E	0.21	SE
16-Dec-2024 00:32:17	19° 13' 45"	-60° 25' 9"	83.76	17.35	1326	243	2.30	NEE	8.95	E	0.25	SE
17-Dec-2024 02:51:50	20° 56' 35"	-55° 13' 9"	102.64	16.76	1615	290	2.16	NE	7.02	NEE	0.13	NNE

Daytime	Latitude	Longitude	Total ME FOC [tn]	Avg. ME FOC [tn/day]	Distance travelled [nm]	Distance daily record [nm]	SWH [m]	Mean Wave Direction From	TWS [m/s]	TWD	Ocean Current Speed [kn]	Mean Ocean Current Direction To
18-Dec-2024 00:36:11	22° 22' 17"	-51° 13' 9"	122.02	21.21	1854	239	2.75	NNE	7.30	NE	0.27	W
19-Dec-2024 00:11:58	24° 0' 59"	-47° 33' 60"	143.10	25.32	2114	260	2.86	NNE	11.53	NE	0.25	SWW
20-Dec-2024 02:06:56	25° 54' 56"	-42° 21' 60"	164.58	18.34	2399	285	2.50	N	3.97	N	0.10	SSW
21-Dec-2024 03:41:04	27° 48' 53"	-37° 9' 60"	184.80	20.05	2680	281	2.73	E	10.61	SEE	0.47	NW
22-Dec-2024 00:42:36	29° 23' 50"	-33° 9' 60"	201.39	18.76	2912	231	2.47	E	7.76	SEE	0.29	NNW
23-Dec-2024 03:59:43	31° 26' 23"	-28° 27' 28"	222.37	17.70	3212	300	2.44	NEE	10.53	NE	0.26	SWW
24-Dec-2024 00:14:46	32° 57' 30"	-24° 27' 28"	238.71	20.49	3434	223	3.30	NE	11.11	NE	0.15	NEE
25-Dec-2024 00:10:03	34° 46' 51"	-19° 15' 28"	256.90	17.20	3698	263	2.16	NNE	5.73	SEE	0.15	N
26-Dec-2024 03:16:03	35° 32' 17"	-13° 12' 26"	275.86	13.76	3996	298	1.48	N	7.13	NE	0.34	SEE
27-Dec-2024 00:23:50	35° 51' 19"	-9° 57' 27"	288.73	16.81	4228	232	2.17	NEE	8.21	E	0.27	SW

Route Plan

<table>
<tr><td>12-Dec-2024 00:30:03 @ (11° 25' 46" , -76° 4' 36")</td><td>13-Dec-2024 00:51:32 @ (13° 35' 21" , -72° 4' 36")</td><td>14-Dec-2024 01:02:53 @ (15° 44' 55" , -68° 4' 36")</td></tr>
<tr><td>
</td><td>
</td><td>
</td></tr>
</table>

15-Dec-2024 02:24:53 @ (17° 48' 3" , -64° 25' 9")	16-Dec-2024 00:32:17 @ (19° 13' 45" , -60° 25' 9")	17-Dec-2024 02:51:50 @ (20° 56' 35" , -55° 13' 9")
		
18-Dec-2024 00:36:11 @ (22° 22' 17" , -51° 13' 9")	19-Dec-2024 00:11:58 @ (24° 0' 59" , -47° 33' 60")	20-Dec-2024 02:06:56 @ (25° 54' 56" , -42° 21' 60")
		
21-Dec-2024 03:41:04 @ (27° 48' 53" , -37° 9' 60")	22-Dec-2024 00:42:36 @ (29° 23' 50" , -33° 9' 60")	23-Dec-2024 03:59:43 @ (31° 26' 23" , -28° 27' 28")
		

<table>
<tr><td>24-Dec-2024 00:14:46 @ (32° 57' 30" , -24° 27' 28")</td><td>25-Dec-2024 00:10:03 @ (34° 46' 51" , -19° 15' 28")</td><td>26-Dec-2024 03:16:03 @ (35° 32' 17" , -13° 12' 26")</td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td colspan="3"></td></tr>
<tr><td colspan="3">27-Dec-2024 00:23:50 @ (35° 51' 19" , -9° 57' 27")</td></tr>
</table>

Annex V – User feedback regarding NTUA Weather Routing Tool

QUESTIONNAIRE REPLY 1

Name: Tsoulakos Nikolaos

Organization: Laskaridis Shipping Co. LTD

Position: Innovation & Technology Manager

- Did you find the installation of the tool easy?
  ☒ Yes
  ☐ No
    - If No, kindly list any problems you faced during the installation

- Did you find the tool easy to use as a first-time user?
  ☒ Yes
  ☐ No
    - If No, kindly list any problems you faced

- Which vessel of your fleet was evaluated using the Weather routing tool?
  M/V KASTOR

- Were you satisfied with the results in Fuel Oil Consumption (FOC) savings which were obtained by the tool?
  ☒ Yes
  ☐ No

- The FOC savings above can be achieved by an optimal route which is around 3hours longer in duration. Is this additional voyage time/distance acceptable considering the savings that are being achieved?
  ☒ Yes
  ☐ No

- Do you think that acceptance of this tool by the Ship's Master shall be
  ☒ Easy
  ☐ Difficult

- Please state a reason

  ____

  ____

  ____

  ____

- Do you have any suggestions for further improvement of the tool and it's functionality?

  To incorporate additional parameters thus enhancing tool's accuracy and to address the need for faster response times.

  ____

  ____

- Would you like to carry out a similar assessment in the future for other vessels of your fleet?

  ☒ Yes

  ☐ No