Mitigating Schedule Delays in Maritime Operations Through Weather-Based Routing Strategies

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Abstract. This study explores the effectiveness of weather-based routing in addressing schedule delays and fuel consumption in maritime operations. Using weather data from the Indonesian Agency for Meteorology, Climatology, and Geophysics, the model calculates resistance factors that influence ship performance. The findings highlight that weather-based routing can mitigate delays caused by adverse weather conditions while improving operational efficiency. Case B as the optimized route according to high wave, despite being longer, mitigates delays by increasing the ship's speed from 12 to 12.7 knots, allowing it to maintain the Estimated Time of Arrival (ETA). This approach demonstrates that adverse weather conditions do not necessarily lead to schedule disruptions. Additionally, this case also achieves a 1.39% improvement in fuel efficiency by considering wave height as a critical factor. Although the savings are modest due to the relatively short sailing distance, the reduction in fuel consumption has a direct impact on lowering emissions, contributing to greener maritime practices. The results underline the potential of weather-based routing to enhance maritime operations by reducing the negative effects of weather on schedule reliability and fuel consumption.

1 Introduction

Maritime transport plays a critical role in global trade, accounting for approximately 80% of goods transported and handling about 10 billion tons of cargo annually [1]. As global trade continues to grow, the demand for maritime transport and shipping traffic is expected to increase significantly in the coming years. Without decisive action and the implementation of additional measures to curb emissions, GHG emissions from the maritime sector are projected to rise dramatically. By 2050, emissions could increase by 90% to 130% relative to 2008 levels, depending on the pace of economic growth and trade expansion [2]. While shipping is recognized as an efficient mode of transport, emitting fewer GHG emissions per tonne-kilometer of cargo transported compared to other modes [3], it still contributed to approximately 3% of global GHG emissions in 2018 [2]. Commercial ships rely on burning fuel as their primary energy source, which results in the release of various air pollutants as

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by-products. The most significant pollutants from shipping activities, with notable impacts on both climate change and public health, also Greenhouse Gases [4], including nitrogen oxides (NOx), sulphur oxides (SOx), and particulate matter (PM). This underscores the urgency of adopting effective strategies to mitigate the sector's environmental impact and ensure sustainable development [2].

The rapid growth of global trade has intensified scrutiny on the maritime industry, driven by increasing demands to reduce ship emissions during operations and at ports. With nearly 70% of emissions occurring within 400 km of coastlines, these pollutants significantly impact air quality, regional climates, and public health in coastal and high-traffic port areas. Addressing these challenges requires substantial reductions in greenhouse gas emissions, which can be achieved through two primary strategies: enhancing ship design to improve propulsion efficiency, reduce resistance, and incorporate alternative energy sources, and implementing operational efficiency measures. These approaches align with efforts to integrate environmental management systems and adopt innovative technologies, as highlighted in recent studies [5]. In recent years, various measures have been proposed to reduce greenhouse gas emissions. These measures can be categorized into two main groups. The first category pertains to ship design improvements, focusing on enhancing propulsion efficiency, reducing overall resistance (hull and propeller), improving engine power performance, and adopting alternative energy sources [6]. The second category involves measures aimed at optimizing operational efficiency [7].

Green shipping, which includes practices like aim to mitigate environmental impacts such as air and water pollution, oil spills, and waste management issues, fostering ecological balance and promoting sustainability in trade [5]. Incorporating green shipping practices aligns seamlessly with weather routing strategies, which optimize voyage plans by leveraging meteorological data to reduce fuel consumption and emissions. By integrating these approaches, the maritime industry can achieve dual benefits: improving environmental performance while enhancing safety and operational efficiency, paving the way for a sustainable future in global trade [8]. The potential reductions achievable through this method have been extensively discussed in studies.

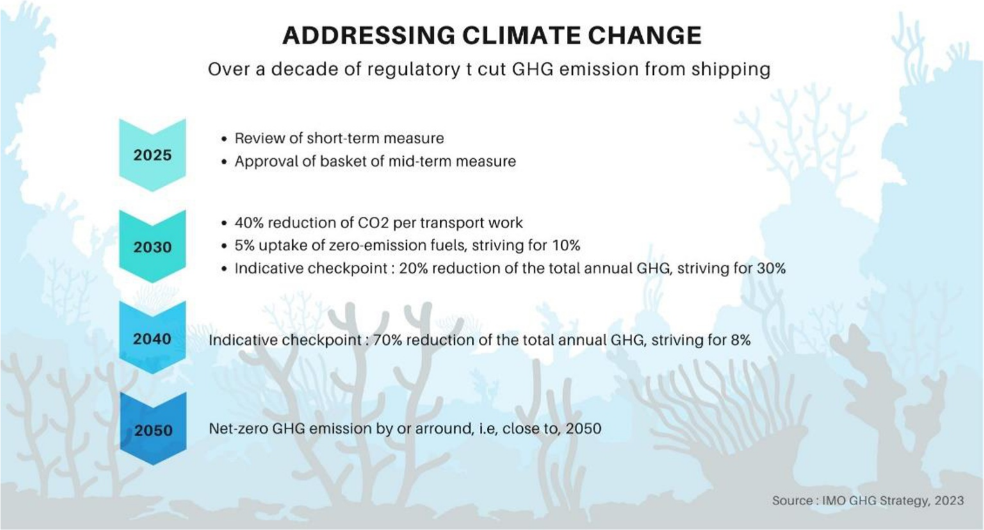
This study builds upon prior unpublished research that investigated the impact of weather variables, such as wind and wave height, on ship performance in the Waingapu-Ende route. The previous findings demonstrated how optimizing resistance in adverse weather conditions could enhance fuel efficiency and operational reliability. Focusing on the same route, this study extends the analysis to address scheduling challenges caused by unpredictable weather. The Waingapu-Ende route, a vital maritime corridor in Indonesia, was selected due to its frequent shipping traffic and significant weather-related disruptions. A map outlining the geographical layout of this route and its environmental conditions is provided in the result and discussion to support a deeper understanding of the study's context.

Building upon insights from previous research, this study shifts its focus from minimizing resistance to optimizing maritime routes, addressing broader challenges in scheduling reliability and operational performance under adverse weather conditions. The Waingapu-Ende route, with its frequent traffic and weather-related disruptions, serves as a relevant case study. This research integrates real-time weather data from Indonesia's Meteorology, Climatology, and Geophysics Agency (BMKG) to develop a model that evaluates the impact of critical variables—such as wind, wave height, and ocean currents—on Estimated Time of Arrival (ETA). By optimizing routes, the study aims to minimize delays, fuel consumption, and emissions, aligning with green shipping practices to enhance both operational efficiency and sustainability in maritime logistics.

2 Literature Review

In general, weather routing studies and implementations are designed to support environmental protection efforts, with the primary aim of reducing the environmental impact of shipping operations. While some optimizations focus on operational costs, these efforts are inherently linked to environmental outcomes. This aligns with the maritime industry's commitment to supporting the IMO's target of net zero emissions by 2050, as shown in Fig. 1. Weather routing has evolved through two generations: the first aimed at minimizing voyage duration and fuel consumption, while the second incorporates ship performance under varying sea conditions, leveraging advanced tools like dynamic programming, genetic algorithms, and pathfinding methods to achieve both economic and ecological benefits [9].

The weather routing problem has been addressed in two distinct generations of approaches. The first generation primarily focused on minimizing voyage duration and fuel consumption, often overlooking the effects of route selection on ship performance in different sea conditions. In contrast, the second generation of weather routing algorithms has taken a broader approach, incorporating ship seakeeping abilities alongside fuel efficiency. These more advanced methods, which include dynamic programming, genetic algorithms, and pathfinding techniques, aim to optimize the voyage by considering a wider range of factors impacting the ship's performance and overall operational efficiency [10].



ADDRESSING CLIMATE CHANGE

Over a decade of regulatory t cut GHG emission from shipping

2025
- Review of short-term measure
- Approval of basket of mid-term measure

2030
- 40% reduction of CO2 per transport work
- 5% uptake of zero-emission fuels, striving for 10%
- Indicative checkpoint : 20% reduction of the total annual GHG, striving for 30%

2040
Indicative checkpoint : 70% reduction of the total annual GHG, striving for 8%

2050
Net-zero GHG emission by or arround, i.e, close to, 2050

Source : IMO GHG Strategy, 2023

Fig. 1. IMO's Timeline

2.1 First Generation

First-generation weather routing refers to the early methods used to predict and optimize sailing routes by considering weather conditions. Generally, these methods were simpler and did not account for dynamic factors or the complex interactions between weather and ship performance. Here are the first-generation weather routing methods.

1. Isochrone Method by James, 1957
   Used for estimating optimal routes based on specific weather conditions [11].
2. Turning Penalties by Lee, 1961
   Optimizes ship routes by considering turning penalties, indirectly contributing to more accurate Estimated Time of Arrival (ETA) predictions [12].
3. Modified Isochrone Method by Hagiwara, 1989

An improvement of the original isochrone method for weather routing optimization [13].

These methods primarily focused on static weather conditions and did not account for dynamic factors like speed changes or fuel consumption.

2.2 Second Generation

Second-generation weather routing methods build upon the first generation by incorporating more dynamic factors, such as adjusting ship speed, fuel consumption, and real-time weather conditions. These methods are more complex and aim to optimize both the route and the operational parameters of the ship, like speed, in response to changing environmental conditions.

1. Weather Routing with Dijkstra Algorithm by Sen and Padhy, 2015
   Used the Dijkstra algorithm for weather routing, integrating real-time weather data for route optimization [14].
2. A-star Algorithm and Wind-Assisted Propulsion by Bentin et al., 2016
   Applied the A-star algorithm and examined the impact of wind-assisted ship propulsion within a weather-routing optimization tool to reduce fuel consumption[15].
3. Simultaneous Route and Speed Optimization by Zaccone et al., 2018
   Used dynamic programming for simultaneous optimization of both route and speed, considering available forecast maps[16].
4. Genetic Algorithm for Minimum Travel Time by Wang et al., 2020
   Introduced a new genetic algorithm that optimized the route for minimum traveling time while accounting for involuntary speed loss due to wind and waves[17].

3 Methodology

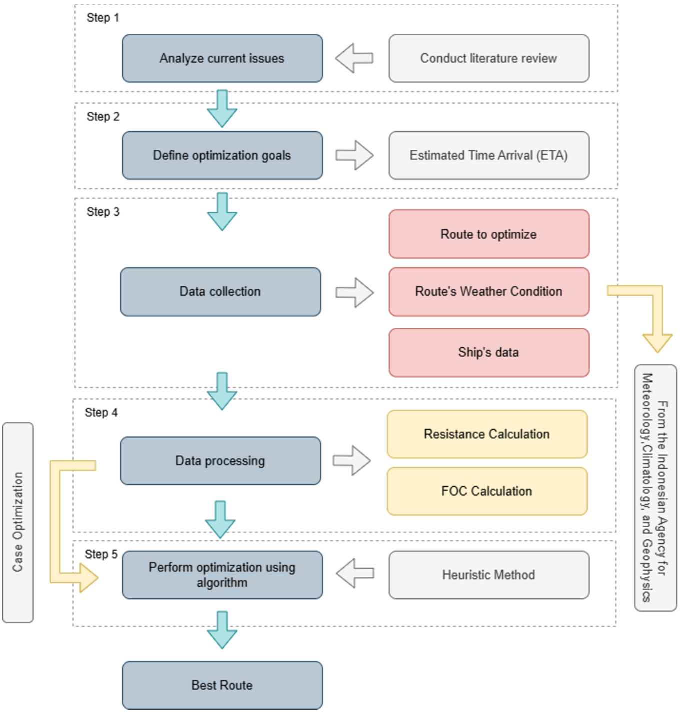


Fig. 2. Research's Flow of Work

The developed methodology is outlined below in Fig 2. The methodology executed in Python involves several key steps to achieve the primary goal of identifying the optimal route within Estimated Time of Arrival (ETA) constraints. The research begins by analyzing the environmental issues and IMO emission targets, proposing weather routing as a solution. Adverse weather conditions are identified as factors causing ETA delays. Data is then collected, including shipping routes and vessel specifications, and processed to calculate resistance and fuel consumption. Heuristic method implemented in Python, is employed to determine the optimal route under the ETA constraint. The final output is the best route derived from the case study.

When planning a ship's route, several criteria must be considered to ensure safety, efficiency, and timeliness. These factors help mitigate risks and optimize the voyage. The key criteria include a few points as follows [18].

1. Navigational hazards, such as potential obstacles or dangerous areas along the route.
2. Water depth, ensuring the vessel can safely navigate without running aground.
3. Tidal variations, considering the height of sea levels that may impact port access or shallow areas.
4. Weather and climate conditions, accounting for storms, winds, and seasonal variations that could affect the journey.
5. Estimated voyage time, calculating the expected duration to meet schedules or delivery deadlines.

As highlighed from above, it is crucial to consider the various obstacles that a ship may encounter during its voyage to ensure safe, efficient, and timely operations. These challenges, including navigational hazards, water depth, tidal variations, weather conditions, and estimated voyage time, must be evaluated to minimize risks and optimize the journey. Fig. 3 provides a simplified presentation of these obstacles, highlighting the key factors that need to be addressed during route planning for a successful maritime operation.

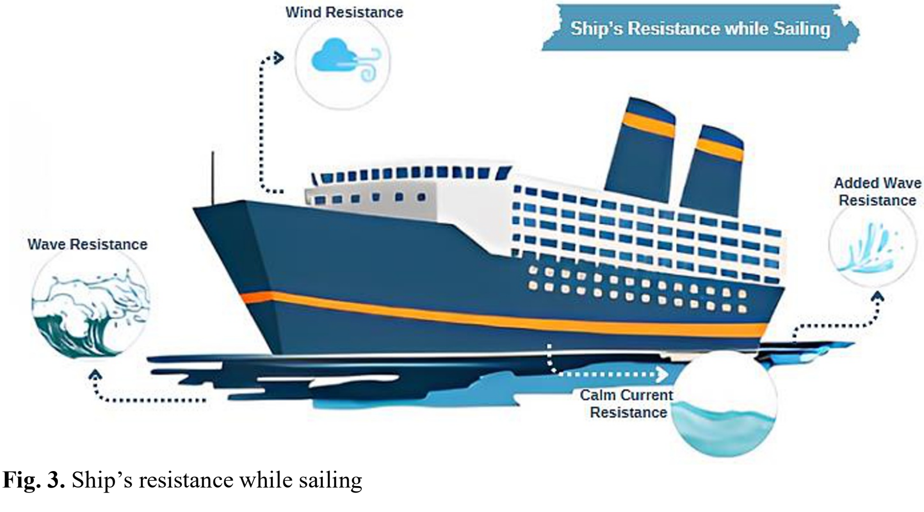


Fig. 3. Ship's resistance while sailing

Weather routing has become an essential tool in contemporary maritime operations, focused on optimizing vessel voyages by incorporating various environmental factors such as weather conditions, navigational hazards, and sea state. This approach utilizes advanced algorithms and weather data to improve the efficiency of maritime transport by minimizing fuel consumption, reducing emissions, and ensuring timely arrivals. By considering factors like wind, wave height, and ocean currents, weather routing can help vessels avoid adverse conditions, optimize fuel usage, and improve overall operational efficiency. In previous studies [19], the framework for weather routing has been well-established, outlining the steps involved in determining the most efficient and environmentally friendly route. The process typically starts with selecting the route to be optimized, with the initial and final points clearly defined. Ship-specific data is then incorporated to estimate the resistance encountered by the vessel, which is significantly influenced by the prevailing weather conditions along the route. To provide accurate and reliable weather data, agencies such as the Indonesian Agency for Meteorology, Climatology, and Geophysics used in this study to get crucial information about weather, including details on wave, wind, and current conditions, which later is used to calculate ship's resistance.

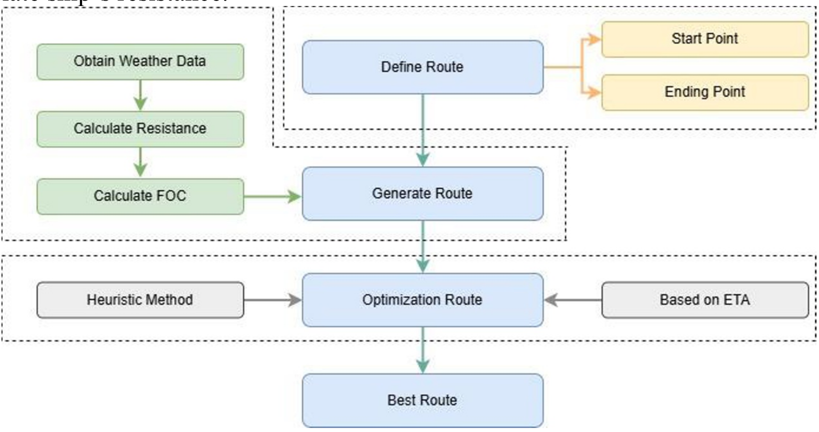


Fig. 4. Weather Routing's Framework

The objective of this study is to optimize the route with respect to the Estimated Time of Arrival (ETA) while considering environmental constraints such as fuel consumption and emissions. A selected optimization algorithm is applied, with distance constraints set to ensure the route is as short as possible while also minimizing emissions. This approach ultimately aims to achieve a balance between operational efficiency and environmental sustainability. The full flow of the weather routing methodology, including all necessary steps and considerations, is visually represented in **Fig. 4.**

3.1 Weather Data

Most weather data providers use a similar approach, as outlined in [19], where weather data, including wave, wind, and current information, is available at various temporal and spatial resolutions. Temporal resolution refers to how frequently the weather data is updated for a specific location, with lower resolution potentially leading to inaccurate estimations due to the dynamic nature of weather. Conversely, higher resolution may not significantly improve accuracy but can increase computational time. Spatial resolution relates to the distance between grid points where weather data is provided. If wave, wind, and current data are not available at the same resolution, the primary grid for optimization is based on the wave data's spatial resolution. As the ship crosses each grid square, intersection points are identified, and wave data is interpolated using linear methods. Wind and current values are also interpolated based on the nearest grid cells. Between intersection points, weather conditions are assumed constant, which is valid for high-density grids. This study uses data from the Indonesian Agency for Meteorology, Climatology, and Geophysics, along with geographical information from Google Maps.

3.2 Map Setting & Routes Generation

In the map setting for weather routing, geographical information is obtained from Google Maps. One of the most critical components of the map setting is determining the appropriate scale and grid that will accurately represent the area of interest. For this study, a scale of 1:10,000 is chosen. The selection of this scale is a fundamental decision, as it directly impacts the granularity and accuracy of the weather data and route analysis. The scale must be chosen based on the distance between the departure and arrival ports. If the ports are relatively close to each other, a larger scale can be applied without compromising the accuracy of the analysis, as smaller details are less significant. However, for longer voyages, using a larger scale (which represents a smaller area) may introduce limitations. A scale that is too large could overlook important navigational features, such as obstacles or changes in weather conditions, and result in less reliable weather routing predictions.

In previous studies [19], the consideration regarding the grid form and its impact on the weather routing process has been clearly outlined. The choice of grid resolution is crucial for ensuring accurate data representation and optimal route analysis. **Fig. 5** provides an illustration of the grid form used in the map setting, demonstrating how the spatial resolution is applied to represent the geographical area and how each grid corresponds to specific weather data points. This grid structure is essential for evaluating the route's environmental conditions, ensuring that the weather data such as wave, wind, and current information are appropriately interpolated and applied during the optimization process.

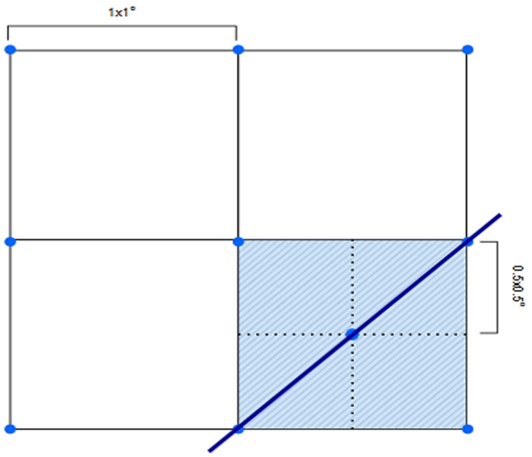


Fig. 5. Inspired by [19], the grid mapping for weather routing is represented by square cells, each corresponding to local weather conditions. The blue line illustrates the ship's route, adjusted to intersect with the center points of the grid, where weather data is interpolated for optimization.

Furthermore, the selection of grid resolution directly influences the quality of the weather routing analysis. The grid must be chosen carefully based on the distance between ports. For shorter distances between ports, a larger grid scale may be sufficient, while for longer distances, a finer grid scale becomes more important to capture the finer variations in weather and ensure more accurate predictions of the route. Therefore, the form and resolution of the grid play a vital role in the precision of the weather routing optimization process, directly affecting both the accuracy of the environmental data and the overall effectiveness of the voyage optimization.

3.3 Resistance Calculation

A method for estimating resistance in calm water conditions, factoring in the effects of currents has been presented by [20]. This approach is known for its reliability in predicting resistance under such scenarios. The equation integrates the speed components and angular direction of the relevant variables in the calculation. The resistance in calm currents includes contributions from viscous resistance, wave resistance, and frictional resistance acting on the vessel. These resistances result from the interaction between the ship and its surrounding environment, considering not only the impact of waves but also the frictional effects between the waves and the ship's hull. The formula used to determine this resistance is detailed in Equation (1).

$$R_{ts_{Calm,current}} = \frac{1}{2}\rho L d U_a^2 X'_{uu} + \frac{1}{2}\rho S U_a^2 C_w + \frac{1}{2}\rho S U_a^2 \Delta C_f \tag{1}$$

As previously illustrated in Figure 3, apart from calm current resistance, a vessel also experiences wind resistance during its voyage, although its contribution is relatively minor. In this study, the wind resistance method proposed by [21] is employed due to its capability to accurately estimate the effects of wind on the vessel. The formula for this calculation is presented in Equation (2).

$$R_{wind} = \frac{1}{2}\rho_a A_T V_{wr}^2 C_{wx}(\chi'_{wind}) \tag{2}$$

One of the significant resistances that represents the interaction between a ship and its environment is added wave resistance. This type of resistance accounts for the additional drag a ship experience when navigating through irregular wave conditions [22]. The calculation of added wave resistance involves an integral that evaluates the contributions of all wave frequencies within the irregular wave spectrum, ranging from zero to infinity. This approach ensures a detailed understanding of how various wave conditions influence the ship's resistance. In this study, the JONSWAP spectrum is utilized to model the added wave resistance. The JONSWAP spectrum is particularly suitable for representing sea states in regions where wind-generated waves are dominant, making it an appropriate choice for the research's specific oceanic conditions [23]. The formula for this calculation is presented in Equation (3).

$$\bar{R}_{aw} = 2\int_0^\infty C_{aw}(\omega_e) S_\zeta(\omega_e) d\omega_e \tag{3}$$

3.4 Fuel Oil Consumption Calculation

$$w_{f0} = P\ x\ SFOC\ x\ \frac{S}{V_s}\ x\ 10^{-6}\ x\ \zeta \tag{1}$$

Referring to [24], the fuel consumption for the main engine can be calculated using Equation 4. The components required to determine the main fuel consumption include the sailing distance and the ship's speed. Additionally, the Specific Fuel Oil Consumption (SFOC) and engine power are variables that represent the type of fuel and the engine's power capacity of the ship.

3.5 Study Case

This study builds on prior unpublished research on resistance optimization for the Waingapu-Ende route, shifting focus to the impact of weather and navigational decisions on Estimated Time of Arrival (ETA), aiming to determine the best route based on ETA and various influencing factors. Previous studies have raised several interesting case studies; however, this research introduces a different approach, particularly concerning the vessel's speed. The three cases analyzed in this study are as follows:

1. Case A: In this case, the vessel does not receive any optimization. It sails at its service speed along the conventional route, as represented by Google Maps.

2. Case B: In this case, the route is optimized by selecting the option with the smallest wave height from all possible alternatives. This optimization aims to minimize disruptions caused by adverse weather conditions, ensuring the vessel can sail safely. To achieve this, the speed will be adjusted so the vessel can maintain its ETA while navigating safely.
3. Case C: In this case, the vessel is set to its normal speed, but the distance is optimized. The route follows the shortest distance without considering weather conditions. As a result, the vessel will meet its ETA but may not sail safely.

Through the analysis of these three scenarios, the study aims to provide deeper insights into speed impacts the ETA and route efficiency. This research focuses on how route selection, distance constraints, and weather optimization can reduce travel time, avoid adverse weather conditions, and ensure optimal efficiency in reaching the destination.

Table 1. Port Coordinate

Port	Coordinate Reference System (CSR)	
	Latitude	Longitude
Start : Waingapu Port	-9.6662	120.2734
Finish : Ende Port	-8.8594	121.6356

As previously mentioned, the Waingapu-Ende route has been selected for this study. This route is particularly significant due to its susceptibility to large waves, influenced by both weather conditions and its geographical location. One of the major consequences of adverse weather is the delay in the vessel's arrival, which can sometimes lead to the complete cancellation of the voyage. These weather-related challenges emphasize the importance of optimizing navigation and timing. **Table 1** present the coordinates of both ports involved in this route.

Table 2. Main Dimension

Main Dimension	Unit	
LOA (Length of All)	55.5	m
B (Breadht)	12	m
H (Height)	3.2	m
T (Draft)	2.4	M
V (speed)	12	kn

The type of vessel used in this study is the ro-ro ferry, as this type of ship is the most operated on the Waingapu-Ende route. The selection of this vessel type is based on the fact that it is the predominant ship navigating through this busy route. Ro-ro ferries are known for their ability to carry passengers and cargo efficiently, making them an essential part of the maritime traffic in this region. **Table 2** is a sample dataset for this type of vessel, which will be used in the analysis.

4 Result & Discussion

In this study, a heuristic approach is applied to optimize route planning. This method selects the most relevant point at each step, enabling the achievement of an efficient solution with relatively short computation time, although it does not always guarantee an optimal solution. The route optimization process is conducted using Python, chosen for its ease of application and its universal nature in algorithm implementation, particularly in the field of optimization.

This study covers three case scenarios, as previously described with their variable in each scenario. The primary objective of this study is to determine the best route based on ETA (Estimated Time of Arrival). Distance and speed are key factors in this analysis, as both influence the ship's arrival time. Therefore, each scenario is designed to explore how the ship's route planning can prioritize ETA, considering the interrelationship between distance and speed. This study presents interesting findings, where conclusions drawn include the criteria for case selection and optimization priorities for route planning in the context of weather routing. The analysis results related to this will be presented in the following sections.

4.1 Optimisation Result

One notable observation from this study is that Case A and Case C produce relatively similar results. This outcome can be attributed to the fact that the optimized routes in Case C is predominantly straight, which limits the influence of route curvature on the optimization process. As a result, the variations between the two cases are minimized, leading to comparable findings. A comprehensive summary of the key insights and conclusions drawn from the research can be found in Table 3.

In the implementation of weather routing, environmental and weather-induced resistance factors are carefully considered to optimize the vessel's route. These resistances directly influence the ship's fuel consumption: the higher the resistance encountered, the more fuel is required to overcome these obstacles. In this analysis, Case A and Case C show identical results in terms of fuel consumption and resistance, which can be attributed to the fact that both routes are optimized to be relatively straight, minimizing the impact of variable weather conditions.

The following graphs depict the levels of resistance the ship faces when navigating through challenging weather conditions, specifically when encountering wave heights in the "rough" range, which can reach up to 3.5 meters. In Indonesian national waters, this is considered a significant wave height, as the seas are generally calm, except during certain periods. Notably, the months of July and August experience the peak of rough seas, with wave heights reaching their highest levels. Additionally, during the West Monsoon period (December–January–February), the highest wave heights are typically observed, as indicated by the January data. These seasonal variations in wave height play a critical role in weather routing optimization, highlighting the importance of accurate weather forecasting and route planning to minimize fuel consumption and improve operational efficiency.

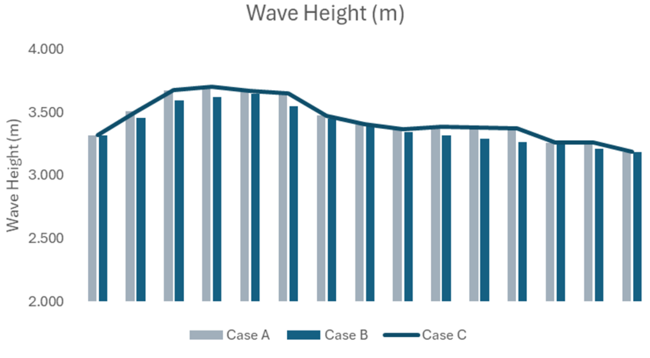


Fig. 6. The wave height encountered by the vessel

The wave height encountered by the vessel along the selected route is presented in **Fig. 6**. Interestingly, the graph does not show a significant variation in wave height, as the route in question is relatively short. Shorter routes tend to experience more stable and consistent weather conditions, which contributes to the minimal fluctuation in wave height observed in the analysis. This consistency suggests that the vessel's exposure to extreme weather events or rough seas is limited, leading to a reduced impact on the overall performance and efficiency of the ship. As such, the influence of wave height on fuel consumption and resistance is less critical in this particular case. However, it is important to note that this finding could vary on longer routes or in regions where more severe and variable weather conditions are common. In these cases, wave height would likely play a more significant role in the optimization process, highlighting the need to account for seasonal weather patterns and route characteristics when evaluating the impact of weather on vessel operations.

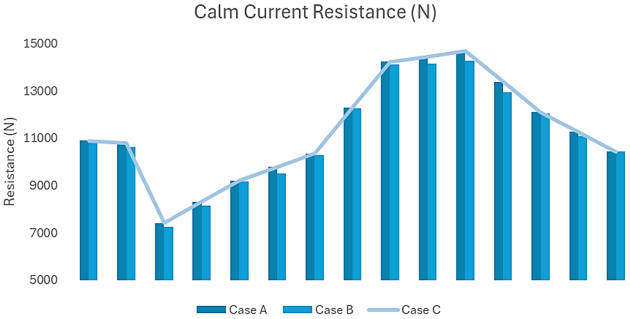


Fig. 7. Calm Current Resistance across three main components: viscous, friction, and wave resistance

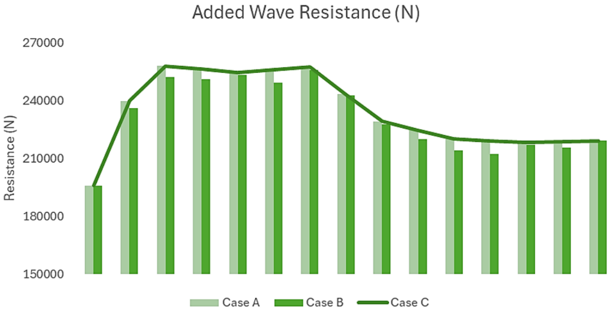


Fig. 8. Added Wave Resistance using the JONSWAP spectrum

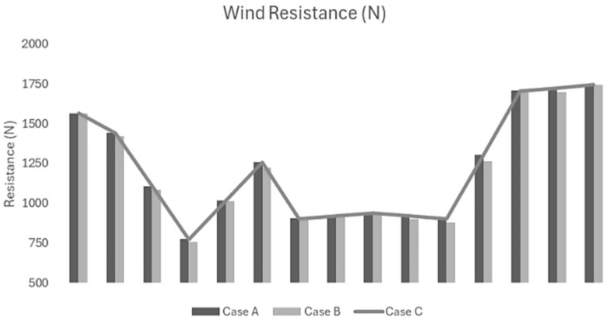


Fig. 9. Wind Resistance highlights the effect of wind conditions on the vessel's overall resistance

As shown in the previously presented resistance analysis graph, the results reflect the local weather conditions encountered by the vessel. Calm Current Resistance is evaluated across three main components: viscous, frictional, and wave resistance, each contributing differently to the total resistance in calm seas. Viscous resistance is caused by the interaction between the ship's hull and the water, frictional resistance arises from friction between the hull and water molecules, while wave resistance is influenced by the ship's interaction with waves. For the cases analyzed, the Calm Current Resistance is 169,6 kN for Case A and C, while it is slightly lower at 166,2 kN for Case B, indicating a minor difference in resistance due to slight variations in sea conditions.

Added Wave Resistance is calculated using the JONSWAP spectrum, a model well-suited to open sea conditions. This spectrum accurately captures wave energy distribution, providing a realistic estimate of the increased resistance the vessel encounters in open seas. For Case A and C, the Added Wave Resistance is 3.512 kN, while for Case B, it is 3.463 kN, indicating a minor increase in wave resistance in the latter case. This difference reflects slight variations in the wave conditions along the route, but the impact on the vessel's resistance is relatively small.

Wind Resistance accounts for the impact of wind on the vessel's overall resistance. In open waters, wind can significantly influence the vessel's speed and fuel efficiency, particularly when sailing at higher speeds. For Case A and C, the Wind Resistance is 18,2 kN, while for Case B, it is slightly lower at 17,9 kN, suggesting that wind conditions may have been somewhat calmer in the second case. Considering wind direction and speed is crucial for route optimization, as it informs fuel consumption estimates and route planning.

The total resistance, including viscous, frictional, wave, and wind resistance, is integrated into the fuel consumption calculations. By multiplying the total resistance by the vessel's speed, engine efficiency, and route distance, this method helps estimate fuel needs and optimize fuel efficiency for the chosen route. The analysis of the resistance components reveals important insights into the factors influencing the vessel's fuel consumption and provides a foundation for effective route optimization strategies.

Table 3 Result from all case

	Case A	**Case B**	**Case C**
Total Resistance (kN)	3700.6	3649	3700.6
Speed (kN)	12	12.7	12
Duration (h)	8.5	8.5	8.5
Distance (nm)	101.5	107.8	101.5
Distance/Speed	8.46	8.46	8.46

The analysis presented in Table 3 provides insights into the outcomes of the weather routing optimization for the given cases, illustrating how each approach influences the vessel's route and voyage duration. In Cases A and C, the results are identical, primarily because the optimized route for Case C matches the conventional route, which is initially a straight line and considered the most distance-efficient. Case C is set with a route distance of 188 km (101.5 Nm), which aligns with the maximum distance of the conventional route. With the same speed and locked distance, the results for Cases A and C are the same due to the initial straight-line route design.

On the other hand, Case B focuses on minimizing wave height along the route, regardless of distance. This approach leads to a longer route of 6.3 Nm (11.66 km), requiring the vessel to increase speed to maintain the ETA. As a result, Case B requires an increased speed of 12.7 knots to ensure timely arrival. This makes Case B a safer and more reliable route, as it prioritizes optimal weather conditions for a smoother sailing experience.

This analysis clearly demonstrates the trade-off between prioritizing favorable weather conditions, such as avoiding rough waves, and maintaining a more direct, distance-efficient route. Case A represents the conventional route, illustrating the shortest distance between the two ports under study. Case B shows the optimized route considering wave height for safer sailing, which requires a speed increase to compensate for the longer distance. Case C, on the other hand, represents the route optimized solely for distance, using Case A's distance as the maximum threshold to define the conventional route's boundary.

The primary goal of this study is to evaluate how weather routing can mitigate delays and improve operational efficiency while balancing fuel consumption and emissions. The outputs from the analysis provide the following key insights :

1. Efficiency in Delays
   Case B demonstrates that delays due to adverse conditions can be mitigated by increasing speed from 12 to 12.7 knots, maintaining the ETA despite longer routes.
2. Fuel Consumption
   By accounting for resistance factors in each case, as well as the S/V ratio (the relationship between distance and travel speed), an efficiency improvement of 1.39% was observed for Case B, which considers wave height as a critical factor. Although this savings appears modest, it reflects the limited variation in wave heights due to the relatively short sailing distance.
3. Emissions
   The reduction in emissions directly correlates with the observed improvement in fuel efficiency. For Case B, the focus on fuel consumption optimization under adverse weather conditions also supports emission reduction goals, aligning with sustainable maritime practices.

According to the study, weather routing can achieve fuel savings of at least 4.9% for the optimal or shortest route, enabling ships to reach their destinations nearly 2 hours faster than conventional routes. Conversely, routes that account for wave height as a safety criterion require 10% more fuel and extend travel time by 22 hours compared to conventional routes at a constant speed [19]. Effective weather routing can reduce a ship's energy consumption by 1% to 5%. Furthermore, the IMO highlighted that weather routing can decrease CO2 and black carbon emissions by 2% to 10%, depending on how these reductions are implemented [25].

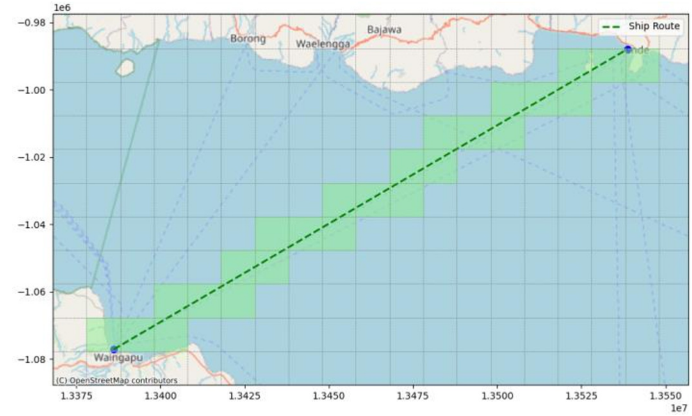


Fig. 10. The main route and the Work Estimated Area (the green grid)

The route optimization visualization in **Fig. 11.** clearly displays three different scenarios: Cases A, B, and C, with a focus on how total resistance influences the selection of the route. The solid red line represents the routes for Cases A and C, which tend to follow a more direct path. In contrast, the purple dashed line represents the route for Case B, which prioritizes avoiding areas with high waves. Case A (as seen in **Fig. 10**) is used as the conventional or baseline route for optimization, divided into 25 grids. Each grid represents a node, resulting in a total of 25 nodes. Each node has a weight representing the total resistance the vessel will experience at that location. This resistance is calculated based on a combination of resistance from calm currents, waves, and wind, which is visualized on the right side of the image as variations in resistance levels across the map.

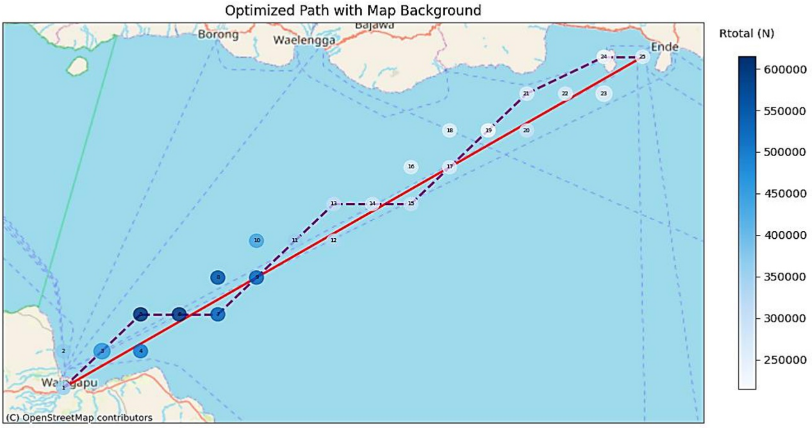


Fig. 11. The route optimization visualization

In Case B, the optimization algorithm is designed to select the path with the lowest resistance between adjacent nodes. Low resistance typically indicates areas with calmer seas and smaller waves. By choosing a route through these nodes, the vessel can avoid larger obstacles, ensuring a safer, more stable, and efficient journey. This process reflects the goal of balancing distance, safety, and energy efficiency as the primary objectives in route optimization. **Fig. 11.** provides a clear comparison of the three route scenarios:

1. Case A: Represents the conventional route with a straight path, used as the baseline for optimization.
2. Case B: The more winding route, considering total resistance. This route is designed to avoid areas with high waves, as shown by the preference for lighter-colored nodes on the map, indicating lower resistance (safe route with ETA).
3. Case C: The optimized route based on distance, which also follows a direct path similar to Case A but gives less consideration to weather conditions or resistance (only focus on ETA without considering safety).

The contrast between Cases B and C reveals differing approaches to weather conditions. Case C focuses on distance efficiency, disregarding safety in areas with high waves, while Case B incorporates weather factors, choosing a longer route to avoid risky areas. Route optimization in Case B showcases how an adaptive algorithm prioritizes safety and comfort, even if it increases travel distance, ultimately reducing fuel consumption and enhancing energy efficiency. The visualization effectively illustrates how the optimization process balances resistance, wave height, and distance to identify the safest and most efficient route.

4.2 Case Discussion

Weather routing optimizes maritime efficiency by leveraging environmental factors to improve fuel consumption, travel time, and safety. Routes best suited for optimization include non-straight paths that can be shortened, longer routes with significant weather variations, areas prone to severe weather, and regions with variable environmental conditions like wind and waves. By avoiding adverse conditions and adjusting speed to maintain estimated arrival times, weather routing minimizes delays and aligns with sustainability goals through reduced emissions. This approach balances operational safety, efficiency, and environmental impact, demonstrating its comprehensive value in maritime operations.

5 Concluding Remarks

This study underscores the critical role of weather routing in optimizing voyage outcomes, particularly in terms of voyage duration, fuel efficiency, and sailing conditions under adverse weather. For instance, Case B demonstrates that delays on longer routes can be avoided by adjusting speed to maintain ETA, achieving 1.39% fuel savings compared to conventional routes due to reduced resistance. These findings underline the importance of integrating real-time weather data, which not only enhances operational performance but also aligns with green shipping initiatives by reducing fuel consumption and emissions. The study's implications extend beyond this specific case, suggesting that adaptive weather routing strategies can be effectively applied to similar maritime scenarios, especially for routes prone to significant wave variations or unpredictable weather. By emphasizing the need for voyage-specific adaptability, this research contributes to the broader adoption of sustainable and efficient practices in maritime operations.

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