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Modeling Shipping Route Optimization Based on Seasonal Ocean Current Variability Using the Ant Colony Algorithm

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Abstract

Indonesia possesses dense and strategic shipping lanes, where seasonal ocean currents in the Java Sea frequently impact vessel transit times. On palm-oil shipping routes from Kumai to various ports in Java, route efficiency is paramount as fuel constitutes the largest operational expense. Due to the variability of ocean currents, conventional routes are not always the most efficient choice. This study utilizes 2024 ocean-current data from the Copernicus Marine Service alongside the technical specifications of the MT Nusaniwe to calculate effective speed, travel time, and fuel consumption. The Ant Colony Optimization (ACO) algorithm is applied to evaluate alternative route combinations under varying seasonal current conditions. The methodology encompasses current analysis, effective-speed formulation, fuel-consumption modeling, and route-optimization simulations for both the northwest and southeast monsoon seasons. Previous literature has not integrated ACO with seasonal oceanographic data for route optimization, which defines the research gap addressed herein. The results demonstrate that ACO-based routes integrated with oceanographic data outperform conventional routes, achieving significant reductions in transit time and fuel consumption. Consequently, this model proves that leveraging seasonal currents can enhance vessel operational efficiency and support data-driven voyage planning.

1. Introduction

Maritime transportation plays a strategic role in supporting economic activities, particularly in archipelagic countries such as Indonesia, where sea routes serve as the primary means of inter-island connectivity. The efficiency of maritime transportation is strongly influenced by environmental factors, especially ocean current characteristics, which directly affect vessel speed, voyage duration, and fuel consumption. Navigation practices that do not account for ocean current dynamics may lead to increased operational costs and reduced voyage efficiency [1]. The Java Sea is one of the most important maritime regions in Indonesia, characterized by relatively shallow waters and strong seasonal variability of ocean currents. Previous studies have shown that current patterns in the Java Sea are predominantly controlled by monsoonal wind systems, resulting in significant changes in current direction and magnitude throughout the year [2]. These seasonal variations not only influence physical oceanographic processes but also have direct implications for maritime transportation activities and operational planning [3].

Numerous studies have investigated the characteristics of ocean currents in the Java Sea under various depth conditions and seasonal regimes. The findings indicate that current velocity and direction vary considerably between the west monsoon, east monsoon, and transitional seasons [4]. Such variability may either facilitate or hinder vessel movement depending on route orientation and departure timing. However, despite the availability of extensive scientific knowledge on ocean current dynamics, its practical application in operational ship route planning remains relatively limited. Recent developments in oceanographic data analysis and numerical modeling have enabled more detailed characterization of ocean current variability. Advances in numerical modeling and data-driven approaches, including machine learning techniques, have been successfully applied to analyze sea surface dynamics and current patterns in the Java Sea [5, 6]. These developments provide valuable opportunities to integrate oceanographic information into maritime operational decision-making, particularly for route optimization.

In parallel, optimization techniques have been widely adopted to address complex decision-making problems in transportation and logistics systems. Metaheuristic algorithms, such as Ant Colony Optimization (ACO), have demonstrated strong performance in solving routing and path optimization problems because of their flexibility and capability to handle nonlinear and multi-constraint optimization problems [7, 8]. In maritime and logistics applications, ACO has been successfully implemented for route optimization, distribution planning, and transportation cost minimization [9, 10].

Despite these advancements, studies integrating seasonal ocean current variability with intelligent optimization algorithms for ship route planning remain relatively limited, particularly in Indonesian waters. Although previous studies have investigated ocean current characteristics and route optimization separately, few have incorporated dynamic seasonal oceanographic conditions directly into the optimization process while simultaneously evaluating voyage efficiency in terms of travel time and fuel consumption. Consequently, many existing routing approaches continue to rely primarily on static shortest-distance criteria without explicitly considering the influence of seasonal current variability on ship performance and fuel efficiency [11]. This research gap highlights the need for a more adaptive route optimization framework that integrates realistic oceanographic conditions into maritime navigation planning.

Therefore, this study aims to develop and evaluate a ship route optimization model that integrates seasonal ocean current characteristics with fuel consumption analysis using the Ant Colony Optimization (ACO) algorithm. The Java Sea is selected as the study area because of its dynamic seasonal current variability and its strategic importance for Indonesian maritime transportation. By integrating oceanographic current data with intelligent optimization techniques, this study evaluates the efficiency of optimized sailing routes compared with conventional routes in terms of travel time and fuel consumption under different seasonal conditions. The expected contribution of this research is to provide an integrated decision-support framework for maritime navigation by combining seasonal ocean current information with intelligent route optimization techniques. The proposed framework is expected to assist ship operators, maritime planners, and researchers in improving voyage efficiency, reducing fuel consumption, and supporting more sustainable maritime transportation in Indonesian waters.

The novelty of this study does not lie in the application of the Ant Colony Optimization algorithm itself, as ACO has been widely utilized in transportation and routing optimization problems. Rather, the novelty resides in the integration of realistic seasonal ocean current characteristics of the Java Sea with the ACO-based route optimization framework to evaluate voyage performance simultaneously in terms of travel time and fuel consumption. Unlike conventional routing approaches that primarily consider sailing distance, the proposed framework incorporates dynamic oceanographic conditions into the optimization process, thereby providing a more adaptive and operationally relevant approach for ship route planning in Indonesian waters.

2. Method

2.1. Research Design and Approach

This study used a descriptive quantitative method with a computational modelling approach to analyze shipping route efficiency. The analysis was based on travel distance, seasonal ocean current speed, sailing time, and fuel consumption. The research was conducted as a case study of the MT Nusaniwe operated by PT Nusa Maritim Logistik. The vessel serves domestic distribution routes in the western and central regions of Indonesia. The case study approach was chosen to examine the effect of seasonal ocean conditions on ship operational efficiency under real operating conditions.

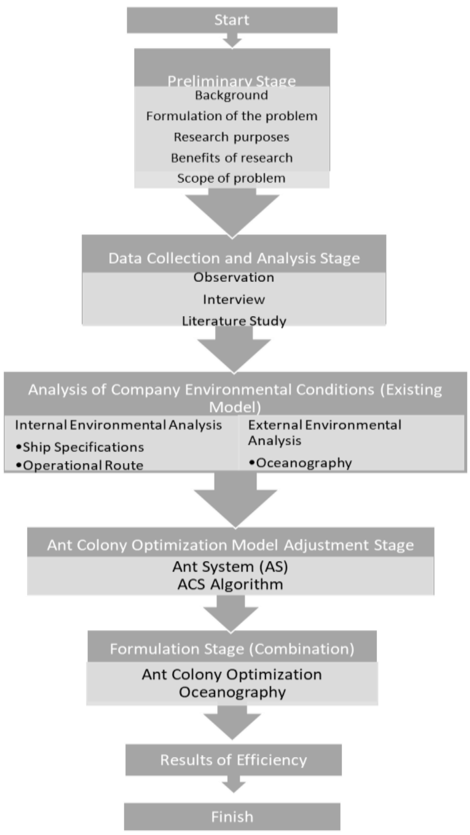

Figure 1. Illustrates the research workflow

The study was carried out at the operational base of PT Nusa Maritim Logistik in Surabaya, Indonesia. The research object was the MT Nusaniwe, a self-propelled oil barge with a capacity of 2,643 GT and 4,222 DWT. The vessel is powered by two Caterpillar 3412 D engines with a total output of 2 × 848 HP and an average fuel consumption of about 3 tons per day. The ship operates on multi-port routes across the Java Sea, connecting Kumai, Semarang, Jakarta, Panjang, Gresik, and Surabaya. This region experiences strong seasonal current variability, which makes it suitable for evaluating environmental effects on sailing performance. The study period was from June to December 2025. This period represents the west monsoon and the east monsoon so that seasonal ocean conditions can be properly represented. The research stages included data collection, ocean current analysis, conventional route modeling, route optimization using the Ant Colony Optimization (ACO) algorithm, and efficiency evaluation of the optimized results. Figure 1 presents the research workflow diagram.

2.2. Seasonal Ocean Current Characteristics

The study area is the Java Sea, one of the most important maritime regions in Indonesia, characterized by shallow waters and strong seasonal variability of ocean currents. The circulation patterns in the Java Sea are predominantly influenced by monsoonal wind systems, resulting in significant changes in current direction and magnitude throughout the year [12]. These characteristics make the Java Sea a suitable region for investigating the influence of seasonal ocean currents on ship route efficiency.Ocean current data used in this study were obtained from previous observational and numerical studies focusing on the Java Sea region. The analysis considers seasonal current characteristics associated with the west monsoon and east monsoon, which have been shown to significantly affect current velocity and direction at different depths. Figure 2 shows the location of the study area at coordinates 105°E–115°E and 2°S–4°S. The current data consists of zonal and meridional velocity components and were used to represent environmental forces acting on the vessel during navigation.

Figure 2. Map of the study area at coordinates 105°E–115°E and 2°S–4°S.

2.3. Ocean Current Data Processing

The dataset used in this study covers the period from 1 January 2024 to 1 December 2024, with a monthly temporal resolution (P1M) and a spatial resolution of 0.083° (approximately ±9 km). The data were downloaded in netCDF format, and all visualization and analytical procedures were conducted using Ocean Data View (ODV) software. In this study, ocean currents were analyzed exclusively at the surface layer, specifically at a depth of 0.49 m below the sea surface. This depth was selected because surface vessels, such as MT NUSANIWE, are predominantly influenced by surface currents during their operational movements. Surface currents represent the most significant oceanographic component affecting sailing efficiency and ship fuel consumption. The spatial domain of the study was defined based on the strategic shipping corridor of the vessel within the Java Sea, bounded by the coordinates 105°E–115°E and 2°S–8°S. This domain encompasses the primary sailing routes connecting the ports of Kumai, Surabaya, Gresik, Semarang, Jakarta, and Panjang. The study area map is presented in Figure 1, which was directly generated from the CMEMS interface. Ocean current patterns were examined using two complementary visualization approaches. Two-dimensional vector maps were employed to illustrate the direction and magnitude of monthly surface currents, while one-dimensional mareograms were used to depict monthly variations of the zonal and meridional current velocity components at selected observation points. Figure 3 shows the Ocean Data View (ODV) interface during the NetCDF dimension selection process, including time, depth, latitude, longitude, and zonal (u) and meridional (v) current velocity components. The processed ocean current data were subsequently used to characterize seasonal surface current patterns and to identify current directions and magnitudes that may support or hinder ship navigation along the study routes. These results form the basis for subsequent analyses related to ship performance and route evaluation under different seasonal oceanographic conditions.

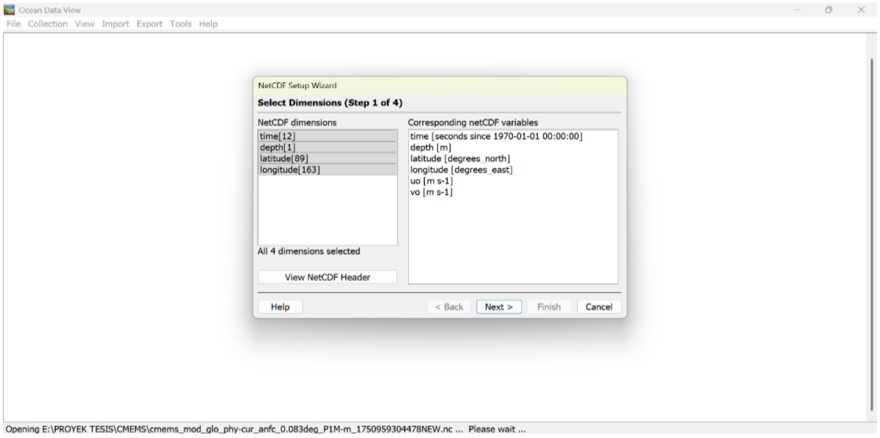

Figure 3. Ocean Data View (ODV) interface during the NetCDF dimension selection process, showing time, depth, latitude, longitude, and zonal (u) and meridional (v) current velocity components.

2.4. Ship Route Optimization Model

The case study vessel represents a commercial tanker operating in the Java Sea. The selected sailing routes connect major ports commonly used in domestic maritime transportation. Route distances and sailing directions were defined based on standard nautical routes and port locations. The influence of ocean currents on ship speed over ground was evaluated by considering the relative direction between ship heading and prevailing current direction, following established approaches in maritime operational analysis.

The route optimization process was performed using the Ant Colony Optimization (ACO) algorithm, a metaheuristic method inspired by the foraging behavior of ants [13]. In this model, each ant represents a potential sailing route between ports. The probability of route selection is governed by pheromone intensity and heuristic information related to route distance and estimated fuel consumption. The pheromone updating mechanism was implemented to reinforce routes with better performance, while evaporation was applied to avoid premature convergence. The optimization process iteratively searches for the route that minimizes fuel consumption while maintaining feasible sailing distances. The application of ACO for routing and optimization problems has been widely adopted in transportation and logistics studies.

The ship route optimization method using the Ant System (AS) algorithm begins with the initialization of algorithm parameters, including the initial pheromone trail intensity between nodes ($\tau 0$) (1), that is updated at each iteration, the number of nodes and inter-node distances (dij) in a symmetric Traveling Salesman Problem (TSP) where $d_{rs} = d_{sr}$, the definition of the starting and destination nodes, the ant iteration constant (Q), the pheromone influence parameter (α) and visibility control parameter (β) with $\alpha > 0$ and $\beta > 0$, the inter-node visibility defined as $\eta_{rs} = 1/d_{rs}$, (2) the number of ants (m), the pheromone evaporation rate (ρ) where $0 < \rho \leq 1$ to prevent unlimited pheromone accumulation, and the maximum number of iterations (NCmax), followed by the random placement of each ant at an initial node among the n nodes, which is recorded as the first element of the tabu list to initiate the route construction process.

$$\tau_0 = \frac{m}{C_{greedy}} \tag{1}$$

$$\eta_{i,j} = \frac{1}{d_{i,j}} \tag{2}$$

$$P_{i,j} = \frac{[\tau_{i,j}]^{\alpha} \cdot [\eta_{i,j}]^{\beta}}{\sum_{k allowed} [\tau_{i,j}]^{\alpha} \cdot [\eta_{i,j}]^{\beta}} \tag{3}$$

The tour length of each ant Pi is calculated after the completion of its respective tour. This calculation is based on the tabu list of each ant and is expressed by Equation (3), which represents the summation of distances between consecutive nodes along the constructed route, including the return distance from the final node to the initial node to form a closed tour.

After the tour length Pi of each ant has been computed, the shortest tour for each iteration can be identified. The overall best tour length obtained throughout the optimization process is denoted as Pij which represents the globally optimal solution achieved by the Ant System algorithm.

2.5. Efficiency Evaluation Method

The performance of the optimized routes was evaluated by comparing them with conventional routes in terms of total sailing distance, travel time, and fuel consumption. Efficiency improvement was quantified as the percentage reduction in fuel consumption achieved by the optimized route relative to the conventional route. This evaluation framework enables assessment of the effectiveness of integrating seasonal ocean current characteristics with optimization algorithms for ship route planning [14].

3. Results and Discussion

3.1. Java Sea Current Patterns

3.1.1. West Monsoon

The West Monsoon occurs from December to February and is characterized by dominant northwesterly winds blowing toward the east to southeast, driven by the pressure gradient between the Asian and Australian continents [15]. This atmospheric circulation strongly controls surface current dynamics in the Java Sea. Analysis of Copernicus Marine Service surface current data for 2024 at a depth of 0.49 m shows that during the West Monsoon, surface currents predominantly flow from west to east, with velocities ranging from 0.20 to 0.40 m/s [16]. This pattern reflects the direct response of ocean currents to intensified monsoonal winds and has a significant influence on maritime navigation. Figure 4 illustrates the West Monsoon surface current pattern during December–February within the geographic domain bounded by 105°E–115°E and 2°S–8°S.

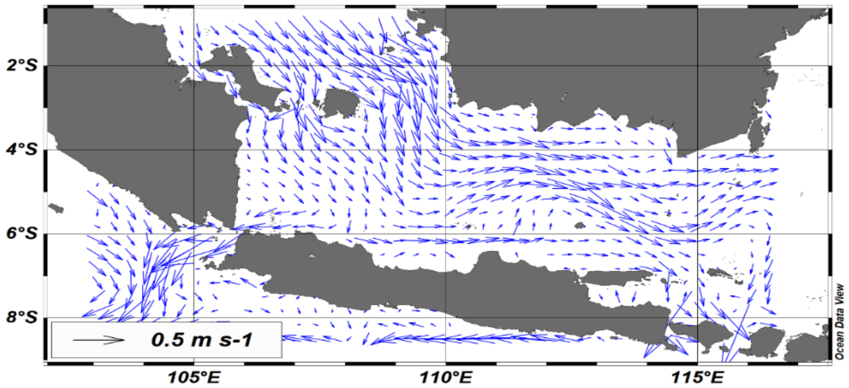

Figure 4. Illustrates the West Monsoon surface current pattern during December–February within the geographic domain bounded by 105°E–115°E and 2°S–8°S.

3.1.2. First Transitional Season

The First Transitional Season (March–May) is marked by weakening monsoonal winds, resulting in variable and less organized surface current patterns in the Java Sea. The lack of a dominant wind direction leads to considerable spatial and temporal variability in current flow. During this season, surface current velocities are generally lower, ranging from 0.10 to 0.25 m/s, which reduces the predictability of current effects on vessel movement and makes navigation efficiency highly dependent on short-term oceanographic conditions and departure timing [17]. Figure 5 shows the surface current pattern during the First Transitional Season (March–May) within the geographic domain bounded by 105°E–115°E and 2°S–8°S.

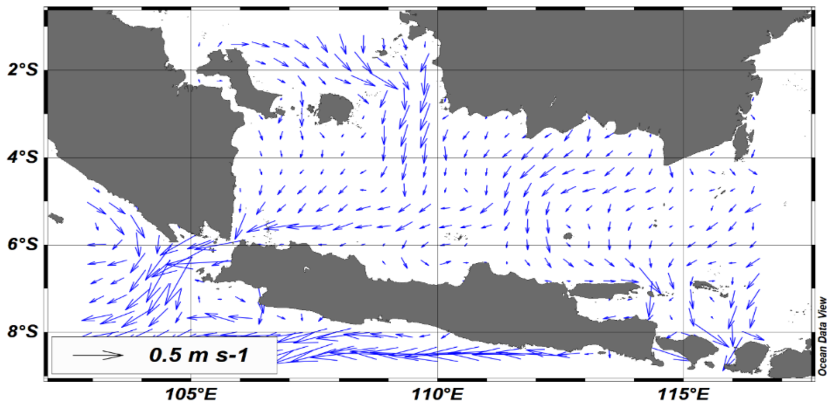

Figure 5. Illustrates the surface current pattern during the First Transitional Season (March–May) within the geographic domain bounded by 105°E–115°E and 2°S–8°S.

3.1.3. East Monsoon

The East Monsoon takes place from June to August and is characterized by southeasterly winds that cause a reversal of surface current direction compared to the West Monsoon, with currents predominantly flowing from east to west. Surface currents during the East Monsoon are relatively more stable, with velocities typically between 0.15 and 0.35 m/s and generally stronger in offshore areas [18]. This consistent pattern may benefit vessels traveling in the same direction as the dominant current while posing challenges for routes oriented towards it. Figure 6 shows the surface current pattern during the East Monsoon (June–August) within the geographic region between 105°E–115°E and 2°S–8°S.

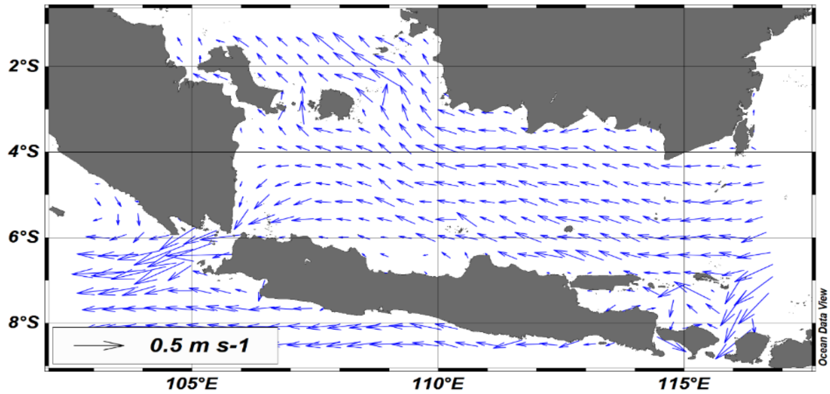

Figure 6. shows the surface current pattern during the East Monsoon (June–August) within the geographic region between 105°E–115°E and 2°S–8°S.

3.1.4. Second Transitional Season

The Second Transitional Season (September–November) represents the transition from the East Monsoon to the West Monsoon and is characterized by weakening and shifting wind systems. Consequently, surface current patterns become increasingly unstable. Current velocities during this season generally range from 0.10 to 0.30 m/s, influenced by local oceanographic dynamics and the early development of the West Monsoon. These conditions make the impact of ocean currents on vessel performance less predictable, emphasizing the need for adaptive route planning. Summary of seasonal surface current velocities in the Java Sea indicates that current speeds range from 0.20–0.40 m/s during the West Monsoon, 0.10–0.25 m/s during the First Transitional Season, 0.15–0.35 m/s during the East Monsoon, and 0.10–0.30 m/s during the Second Transitional Season. Figure 7 shows the surface current pattern during the Second Transitional Season (September–November) over the geographic domain of 105°E–115°E and 2°S–8°S, while Figure 8 depicts the current velocity variations in the east–west (zonal) direction.

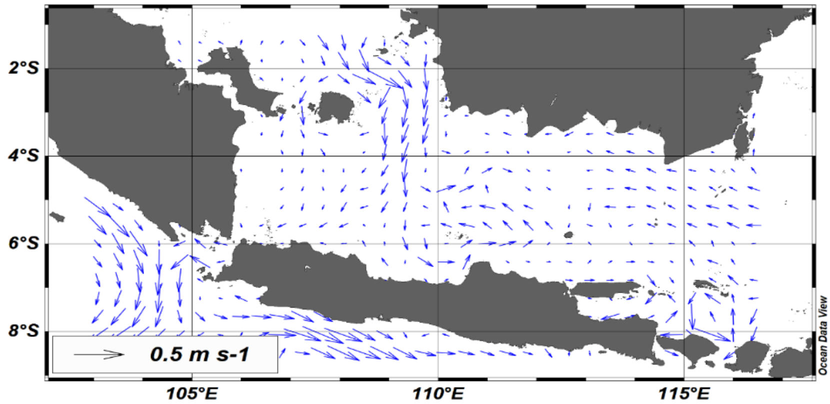

Figure 7. presents the surface current pattern during the Second Transitional Season (September–November) over the geographic domain of 105°E–115°E and 2°S–8°S.

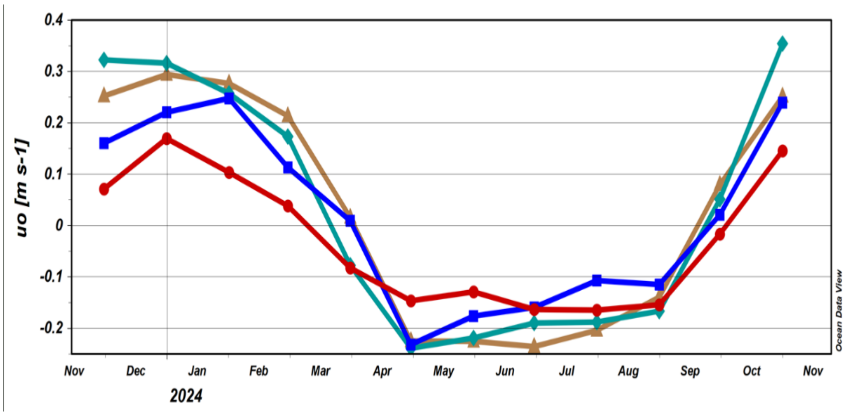

Figure 8. depicts the current velocity variations in the east–west (zonal) direction.

3.2. Ship Route Optimization Model

Shipping route optimization in this study was performed using the Ant Colony Optimization (ACO) algorithm to determine the optimal sailing route based on inter-port distances and route characteristics. In the ACO framework, each ant represents a potential sailing route, which is constructed iteratively according to pheromone intensity and heuristic information derived from the distance between ports. The results of the initial transition probability calculation between ports are presented in Table 1.

Table 1. Results of the initial transition probability calculation

Distance	Surabaya	Gresik	Semarang	Jakarta	Panjang	Max	Destination	Tabu List
Surabaya	0	18.2	0.537	0.255	0.206	18.2	Gresik	1,2
Gresik	0.946	0	0.0292	0.0134	0.01	0.946	Surabaya	2,1
Semarang	0.294	0.307	0	0.234	0.163	0.307	Gresik	3,2
Jakarta	0.14	0.142	0.236	0	0.48	0.48	Panjang	4,5
Panjang	0.13	0.131	0.188	0.549	0	0.549	Jakarta	5,4

The tour length of each ant is calculated after all ants complete their respective tours. The tour length is obtained by summing the distances between consecutive nodes recorded in the tabu list of each ant. Routes with shorter tour lengths are reinforced through the pheromone updating mechanism, thereby increasing their probability of being selected in subsequent iterations. The tour construction results after all ants completed route formation based on inter-city transition probabilities (P_{ij}) are summarized in Table 2.

Table 2. Tour construction results after all ants completed route formation based on inter-city transition probabilities (P_{ij}).

Distance	Surabaya	Gresik	Semarang	Jakarta	Panjang	Destination	Tabu List
Surabaya	0	0	0	0	0.44	Panjang	1,2,3,4,5
Gresik	0	0	0	0	0.42	Panjang	2,1,3,4,5
Semarang	0	0	0	0	0.41	Panjang	3,2,1,4,5
Jakarta	0.496	0	0	0	0	Surabaya	4,5,3,2,1
Panjang	0.498	0	0	0	0	Surabaya	5,4,3,2,1

The ACO results indicate that the algorithm successfully converges toward an optimal solution after several iterations. Compared with the conventional shipping route, the ACO-optimized route produces a significantly shorter sailing distance. The conventional route has a total distance of approximately 1514 km, whereas the optimal route generated by the ACO algorithm is reduced to about 968 km. Based on the optimization results, two equivalent route sequences with minimum total distance were obtained, namely Panjang – Jakarta – Semarang – Gresik – Surabaya – Kumai and its reverse sequence Surabaya – Gresik – Semarang – Jakarta – Panjang – Kumai. These results are further detailed in the cost calculation stage shown in Table 3.

Table 3. Description of the cost calculation stage (minimum total distance)

Ant	Tabu List	Segment Distances (km)				Total Distance (km)
1	1,2,3,4,5	10	324	425	209	968
2	2,1,3,4,5	10	339	425	209	983
3	3,2,1,4,5	324	10	713	209	1256
4	4,5,3,2,1	209	610	324	10	1153
5	5,4,3,2,1	209	425	324	10	968
6	3,4,5,2,1	425	209	870	10	1514

The optimal routes derived from the Ant Colony algorithm are subsequently used as the basis for further analyses, particularly for the evaluation of effective ship speed and operational efficiency in the following sections.

3.3. Efficiency Evaluation

The operational efficiency of MT. *Nusaniwe* was evaluated by comparing the conventional sailing route with the route optimized using the Ant Colony Optimization (ACO) algorithm, as defined in Subsection 4.3, while considering the influence of seasonal ocean currents on vessel performance. On the conventional route with a total distance of 1514 km, the vessel operated at an average speed of 18.52 km/h, requiring 81.7 hours (3 days 9 hours 42 minutes) of sailing time and consuming 10.2 tons of fuel. In contrast, the ACO-based optimization produced a shorter sailing route of 968 km, which was applied under West Monsoon–First Transitional and East Monsoon–Second Transitional conditions. Accordingly, within an annual operational cycle, MT. *Nusaniwe* requires route adjustments only once every six months, following the seasonal reversal of dominant ocean current patterns.

The optimal route for the West Monsoon and First Transitional Season follows Kumai – Panjang – Jakarta – Semarang – Gresik – Surabaya – Kumai, whereas the optimal route for the East Monsoon and Second Transitional Season follows Kumai – Surabaya – Gresik – Semarang – Jakarta – Panjang – Kumai. These two routes represent directionally reversed but distance-equivalent optimal paths, demonstrating that seasonal route switching based on ocean current variability can maintain high operational efficiency while minimizing the need for frequent route reconfiguration and supporting long-term, energy-efficient voyage planning [19, 20]. A comparison of sailing speed and distance under different seasonal conditions is presented in Table 4.

Table 4. Comparison of Sailing Speed and Distance under Different Seasonal Conditions

No	Season	Route Type	Current Condition	Ship Speed	Distance
1	Existing Route	Conventional	–	18.52 km/h	1514 km
2	West Monsoon – First Transitional	Optimized (ACO)	Favorable current (+1.08 km/h)	18.52 + 1.08 = 19.60 km/h	968 km
3	East Monsoon – Second Transitional	Optimized (ACO)	Favorable current (+0.90 km/h)	18.52 + 0.90 = 19.42 km/h	968 km

By utilizing favorable ocean currents along the optimized route, the effective ship speed increased to 19.60 km/h during the West Monsoon–First Transitional period and 19.42 km/h during the East Monsoon–Second Transitional period. Consequently, sailing time was reduced to 49.3 hours and 49.8 hours, respectively, compared to 81.7 hours required for the conventional route. In addition, fuel consumption decreased significantly to 6.17 tons and 6.23 tons, resulting in fuel efficiency improvements of 39.51% and 38.92%. A detailed comparison of sailing time, voyage duration, fuel consumption, and efficiency between the conventional and optimized routes is presented in Table 5.

Table 5. Comparison of Sailing Time, Fuel Consumption, and Efficiency

No	Distance	Sailing Time (hours)	Duration	Fuel Consumption	Efficiency
1	1514 km	81.7 hours	3 days 9 hours 42 minutes	10.2 tons	–
2	968 km	49.3 hours	2 days 1 hour 18 minutes	6.17 tons	39.51%
3	968 km	49.8 hours	2 days 1 hour 48 minutes	6.23 tons	38.92%

4. Conclusion

This study successfully achieved its objective of developing and evaluating a ship route optimization framework by integrating seasonal ocean current characteristics with the Ant Colony Optimization (ACO) algorithm for the operational routes of MT. *Nusaniwe* in the Java Sea. The results demonstrate that incorporating realistic oceanographic conditions into the optimization process provides measurable operational benefits compared with conventional route planning methods that primarily consider sailing distance. The optimized routes effectively utilized favorable seasonal ocean currents, resulting in an increase in the vessel's effective sailing speed of approximately 0.49–0.58 knots (0.90–1.08 km h^{-1}), which consequently reduced voyage duration and improved overall operational efficiency.

The optimization framework produced a substantial reduction in sailing distance from 1,514 km to 968 km and achieved fuel consumption savings of approximately 39% relative to the conventional route. These findings indicate that the integration of seasonal ocean current information with ACO-based optimization can significantly enhance voyage efficiency while reducing operational fuel requirements. Therefore, the proposed approach provides a practical decision-support tool for ship route planning under varying seasonal oceanographic conditions in the Java Sea.

It should be emphasized that the proposed optimization framework is intended as a planning and decision-support approach rather than a universal routing solution. The optimization results depend on the quality and temporal representativeness of the ocean current data used in the analysis and were evaluated for the operational characteristics of MT. *Nusaniwe* within the selected study area. Consequently, the performance of the model may vary under different vessel characteristics, operational constraints, or oceanographic environments.

Overall, this study demonstrates that integrating dynamic seasonal ocean current information into intelligent route optimization represents a practical strategy for improving maritime transportation efficiency. Future research should incorporate additional environmental variables, such as wind, wave conditions, tidal effects, and real-time oceanographic observations, together with multi-objective optimization techniques to produce more adaptive, robust, and operationally applicable ship routing systems for broader maritime applications.

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References

[1] A. Rifai, B. Rochaddi, U. Fadika, J. Marwoto, and H. Setiyono, "Kajian Pengaruh Angin Musim Terhadap Sebaran Suhu Permukaan Laut (Studi Kasus : Perairan Pangandaran Jawa Barat) : "Study of Monsoon Influence on Sea Surface Temperature Distribution (Case Study: Pangandaran Waters, West Java)," *Indonesian Journal of Oceanography*, vol. 2, no. 1, pp. 98-104, Mar. 2020, doi: https://doi.org/10.14710/ijoce.v2i1.7499

[2] Y. N. Sari, A. Wirasatriya, K. Kunarso, B. Rochaddi, and G. Handoyo, "Variabilitas Arus Permukaan Di Perairan Samudra Hindia Selatan Jawa : Surface Current Variability in the Waters of the Southern Indian Ocean of Java," *Indonesian Journal of Oceanography*, vol. 2, no. 1, pp. 1-7, Mar. 2020, doi: https://doi.org/10.14710/ijoce.v2i1.6785

[3] A. Yusron, W. S. Pranowo, Y. Yulianto, and Candrasa, "Karakteristik Gelombang Laut di Teluk Banten dan Sekitarnya pada Monsun Peralihan Berdasarkan Data Model Global : The Characteristics of Sea Waves in Banten Bay and Its Surroundings During The Transitional Monsoon Based on Global Model Data ", *chartdatum*, vol. 10, no. 2, pp. 141–156. 2025, doi: https://doi.org/10.37875/chartdatum.v10i2.364

[4] R. P. Pasaribu, H. Sagala, A. Rahman, and A. Cahyani, "Karakteristik arus Laut Jawa pada musim barat di beberapa kedalaman : Characteristics of Java Sea Currents in the West Monsoon at Several Depths," *Jurnal Teknik Kelautan*, vol. 22, no. 1, 2024, doi: https://doi.org/10.32693/jgk.22.1.2024.823

[5] Y. Suo, L. N. Zhu, Q. G. Zang, and Q. Wang, "An ant colony optimization algorithm for selection problem," *Applied Mechanics and Materials*, vols. 411–414, pp. 1939–1942, 2013. doi: https://doi.org/10.4028/www.scientific.net/AMM.411-414.1939

[6] E. Asmara and B. P. Ichtiarto, "Penerapan p-Median terhadap optimasi alokasi dan lokasi distribution center pada Sistem Logistik Pedesaan di Indonesia : Application of p-median to optimization of allocation and location distribution center in rural logistics system Indonesia," *Operations Excellence*, vol. 13, no. 2, pp. 215–222, 2021, doi: https://doi.org/10.22441/oe.2021.v13.i2.020

[7] A. Ihsan, T. A. Adlie, and S. Harliansyah, "Optimalisasi pencarian jalur terpendek mobile robot menggunakan metode Ant Colony Optimization : Shortest Path Search Optimization for Mobile Robots Using the Ant Colony Optimization (ACO) Method," *Techné*, vol. 23, no. 1, pp. 39–54, 2024, doi: https://doi.org/10.31358/techne.v23i1.389

[8] B. Vernimmen, W. Dullaert, and S. Engelen, "Schedule unreliability in liner shipping: origins and consequences for the hinterland supply chain," *Maritime Economics & Logistics*, vol. 9, no. 3, pp. 193–213, 2007, doi: https://doi.org/10.1057/palgrave.mel.9100182

[9] H. Wang, O. L. Osen, G. Li, W. Li, H.-N. Dai, and W. Zeng, "Big data and industrial Internet of Things for the maritime industry in Northwestern Norway," in *TENCON 2015 - 2015 IEEE Region 10 Conference*, 2015, pp. 1–5, doi: https://doi.org/10.1109/TENCON.2015.7372918

[10] Z. Tian, F. Liu, Z. Li, R. Malekian, and Y. Xie, "Development of key technologies in vessels connected to the Internet," *Symmetry*, vol. 9, no. 10, Art. no. 211, 2017, doi: https://doi.org/10.3390/sym9100211

[11] A. Hlali and S. Hammami, "Seaport concept and services characteristics: Theoretical test," *The Open Transportation Journal*, vol. 11, no. 1, 2017, doi: https://doi.org/10.2174/1874447801711010120

[12] W. Abigail, M. Zainuri, and W. S. Pranowo, "Studi Tentang Produktivitas Primer Berdasarkan Distribusi Nutrien dan Intensitas Cahaya di Perairan Selat Badung, Bali : Study on Primary Productivity Based on Nutrient Distribution and Light Intensity in Badung Strait Waters, Bali," *Journal of Oceanography*, vol. 4, no. 1, pp. 150 - 158, Jan. 2015

[13] J. Zaucha and M. Matczak, "Role of maritime ports," *SHS Web of Conferences*, vol. 58, Art. no. 01033, 2018. doi: https://doi.org/10.1051/shsconf/20185801033

[14] T. Wang, J. Liu, and F. Zeng, "Application of QFD and FMEA in ship power plant design," in *Proc. ISCID*, 2018. doi: https://doi.org/10.1109/ISCID.2017.219

[15] C. Jiang, S. Fu, and Y. Yu, "Risk identification analysis of fire accidents for passenger ships by FMEA," in *Proc. ICTIS*, 2023. doi: https://doi.org/10.1109/ICTIS60134.2023.10243781

[16] B. O. Ceylan, D. A. Akyar, and M. S. Celik, "A novel FMEA approach for risk assessment of air pollution from ships," *Marine Policy*, vol. 150, Art. no. 105536, 2023. doi: https://doi.org/10.1016/j.marpol.2023.105536

[17] C. Fan, J. Montewka, and D. Zhang, "Risk prioritization in autonomous ship operational modes using FMEA," in *Proc. ICTIS*, 2021. doi: https://doi.org/10.1109/ICTIS54573.2021.9798656

[18] Y. E. Priharanto *et al.*, "Risk assessment of the fishing vessel main engine by fuzzy-FMEA approach," *Journal of Failure Analysis and Prevention*, vol. 23, no. 2, pp. 697–706, 2023. doi: https://doi.org/10.1007/s11668-023-01607-w

[19] L. Huang, "A mathematical modeling and optimization algorithm for marine ship route planning," *Journal of Mathematics*, vol. 2023, Art. no. 5671089, 2023. doi: http://doi.org/10.1155/2023/5671089

[20] X. Zhang, Y. Wang, and D. Zhang, "Location-routing optimization using hybrid ant colony algorithm," *Mathematics*, vol. 12, no. 12, Art. no. 1851, 2024. doi: https://doi.org/10.3390/math12121851