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Sefer planlamasında gemilerin karbon ayak izinin azaltılması: Atlantik geçişi üzerine bir vaka çalışması

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ÖZET

Sefer planlaması sırasında hem emniyetli hem de yakıt tasarrufunun sağlanması açısından en verimli gemi rotalarının belirlenmesi büyük önem taşımaktadır. Büyük daire seyri ve Hava durumu yönlendirmesi, denizciler tarafından okyanus geçişleri için kullanılan en yaygın iki yöntemdir. Büyük daire seyri, uzun mesafelerde daha kısa rotaları takip ederek zamandan ve yakıttan tasarruf etme potansiyeliyle bilinir; ancak daha yüksek enlemlerde seyredilmesi nedeniyle gemileri olumsuz hava koşullarına ve deniz durumlarına maruz bırakabilir. Öte yandan, hava durumu yönlendirmesi, potansiyel olarak daha uzun da olsa daha emniyetli rotaları belirlemek için pilot haritaları ve meteorolojik verileri entegre ederek sert hava koşullarıyla ilişkili riskleri en aza indirir. Bu çalışma, belirli bir zaman diliminde batıya doğru Atlantik okyanusu seferi yapan handy-size bir tankerin rota planlamasına odaklanmaktadır. Çalışmanın temel amacı bu iki yöntemin etkinliğini değerlendirmektir. Büyük daire seyri rota bileşenleri küresel trigonometri denklemleri kullanılarak hesaplanırken, hava durumu rota planlaması pilot haritaları ve meteorolojik veriler kullanılarak belirlenmiştir. Transas Köprüüstü Simülatöründe (NTPRO 4000) çevresel koşullar oluşturuldu ve test edildi. Sonuçlar, Hava durumu yönlendirmesi yönteminin GC'ye göre %21,3 daha yüksek enerji verimliliği sağladığını ortaya koymaktadır. Bu araştırmadan elde edilen bilgiler, ticari gemilerin operasyonel verimliliğinin ve emniyet standartlarının artırılmasına önemli ölçüde katkıda bulunuyor.

Anahtar Kelimeler: Karbon ayakizi, büyük daire seyri, hava durumu yönlendirmesi, sefer optimizasyonu, denizcilikte enerji verimliliği, operasyonel enerji verimliliği (EEOI)

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Research Article

Reducing carbon footprint of ships in voyage planning: a case study of Atlantic passage

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ABSTRACT

Determining the most efficient ship routes is crucial to ensuring both safety and fuel savings during voyage planning. Great circle navigation and weather routing are the two most common methods used by navigators for ocean crossings. Great circle navigation is renowned for its potential to save time and fuel by following shorter routes over long distances; however, it may expose vessels to adverse weather conditions and sea states owing to navigation at higher latitudes. However, weather routing integrates pilot charts and meteorological data to identify safer routes, albeit potentially longer ones, minimizing the risks associated with rough weather. This study focuses on route planning for a handy-sized tanker that contracts a westbound Atlantic ocean voyage within a specific timeframe. The main objective of this study is to evaluate the efficacy of these two methods. The great circle route components were computed using spherical trigonometry equations, whereas weather routing planning relied on pilot charts and meteorological data. The environmental conditions were simulated and tested using a Transas Full Mission Simulator (NTPRO 4000). The results reveal that the WR method provides 21.3% higher energy efficiency the GC. The insights derived from this study contribute significantly to enhancing the operational efficiency and safety standards of commercial vessels.

Keywords: Carbon footprint, great circle sailing, weather routing, voyage optimization, energy efficient shipping, EEOI

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1. Introduction

In the modern world, ship navigation relies heavily on advanced technologies. In recent years, improved communication capabilities, along with greater accessibility to trustworthy weather forecast data, have resulted in safer and more effective ship voyage planning. However, navigational safety is still strongly dependent on comprehensive voyage plans and a master's ability to make sound judgments. According to the International Convention for the Safety of Life at Sea, before departing a voyage, masters should ensure that every step of the voyage, from berth to berth, is planned using updated nautical charts at a suitable scale and navigational publications. Furthermore, ocean passages have special aspects of voyages that must be planned differently from restricted waters because of the large distance between search and rescue units and the aim of energy efficiency.

Fuel-efficient planning of ship voyages within the maritime industry has become a crucial factor for reducing the carbon footprint. In this regard, two approaches that ship masters might utilize when planning an efficient ocean passage stand out: the Great Circle (GC) route and Weather routing (WR). The GC Route aims to minimize fuel consumption by traversing shorter distances, whereas WR guides ships to choose more efficient routes based on weather conditions, thereby lowering carbon emissions. GC is one of the most commonly used methods for crossing the oceans (Wang et al., 2020). The routes determined using equations or special charts created using gnomonic projection provide the shortest routes between the two locations on Earth's surface (Bowditch, 1977). GC involves calculating a vessel's course using trigonometric functions and axioms. Traditional methods use spherical trigonometry, Haversine formulas, and the Napier Wheel (Tseng et al., 2013; Baric et al., 2021). Additionally, recent studies have discovered methods derived from vector analysis and calculations to determine the distance and courses of a GC (Hsu et al., 2017; Iphar & Jousselme, 2023; Hsieh et al., 2023). Because GC routes evolve convexity towards the poles, increasing latitude increases the probability of encountering bad weather. To avoid the risks posed by bad weather, safe route options should be studied by evaluating up-to-date data using a WR approach. Ship WR focuses on optimizing ship routes based on meteorological and oceanographic data. It aims to reduce fuel usage, minimize cargo and hull damage, and enhance safety (Simonsen et al., 2015; Skoglund et al., 2015; Perera & Soares, 2017; Chen et al., 2019) . Weather forecasting services for ship routing have become critical to a variety of navigational and ocean engineering research issues. Various optimization algorithms and weather forecasts are used in the routing process (Walther et al., 2016; Wang et al., 2018; Zis et al., 2020; Kytariolou & Themelis, 2022; Zhao et al., 2022). The selection of the optimization algorithm and input parameters is crucial for the effectiveness of the WR system. Numerous services provide a diverse range of weather predictions, incorporating original and post-processed data from numerous sources. These services differ in terms of update frequency, area coverage, geographical resolution, investigated natural phenomena, and output file formats (Życzkowski et al., 2019). Ship meteorological navigation involves route planning before sailing and route correction during navigation, based on real-time weather information. Kobayashi et al. (2015) proposed a weather-routing optimization technology that reduces fuel consumption and EEOI.

This research compares the GC with WR methods for crossing the Atlantic Ocean: one employs shorter routes in more challenging sea conditions, while the other uses longer routes in better sea conditions. The comparison focused on three key performance criteria for optimization: CO2 emissions, arrival time, and fuel economy. In doing so, it aims to contribute significantly to making more informed and efficient decisions in reducing carbon footprints within the maritime industry. GC is one of the most commonly used methods for crossing the oceans comparing the GC and WR methods have focused on the underwater hydrodynamics of ships by employing mathematical methods (Lin et al., 2013; Pennino et al., 2020; Wang et al., 2020); however, little information is available on the factors influencing ship speed, such as ocean mass currents, wind-driven surface currents, and wind resistance due to the structure of the ship. Furthermore, while it is commonly recognized that data on the main engine continuous rate and speed relations for various ship navigation situations are required for fuel consumption and sailing time calculations, it has been discovered that this information is not provided in adequate detail. Previous studies have utilized different equations to account for the impacts of the sea and waves on average ship speeds. Unlike previous studies, in this study, all projected conditions, such as auto pilot response and paddle effect for both navigation methods, were examined using the Transas Full mission simulator (NTPRO 4000), and the average speed was determined. The remainder of this paper is organized as follows: First, an overview of the methodology used for the comparison described in this study is given in Section 2. The results and discussion will delve into key metrics, such as fuel consumption, emissions levels, cost implications, and environmental sustainability aspects associated with each routing method, which are presented and discussed in Section 3. In the last section, the author presents his conclusions and suggestions for future studies.

2. Materials and Methods

The shortest distance between two locations on the globe is the GC arc connecting them; therefore, the GC method is often preferred for ocean crossing. Because each longitude is a GC arc, the distance between the rhumb line and the GC is minimal when navigating between the 000° and 180° routes. The advantage was greatest when sailing near the east 90° and west 270° courses (Bowditch, 1977). Various equations have been proposed to generate the GC equation (Miller, 1991; Earle, 2005; Earle, 2006). In the Northern Hemisphere, the arc between locations A and B creates a GC track (Figure 1).

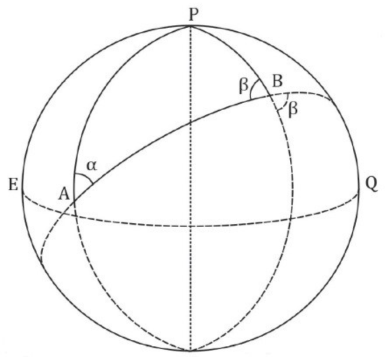


Figure 1. GC elements in the Northern Hemisphere

The latitude of departure (LatA), latitude of destination (LatB), and the difference in longitude between departure and destination (DlongAB) are all known. GC can be solved using spherical trigonometry equations. If the departure and arrival latitudes are in the same hemisphere, the GC(dist) distance can be determined as follows:

$$Cos\ dist = (SinLatA.SinLatB) + (CosLatA.CosLatB.Cos\mathrm{DlongAB}) \quad (1)$$

where α represents the inner angle of the spherical triangle at the departure position.

$$\alpha = \text{Cos}^{-1}\left(\frac{SinLatB-(SinLatA.Cosdist)}{CosLatA.Sindist}\right) \tag{2}$$

β represents the inner angle of the spherical triangle at the destination position.

$$\beta = \text{Cos}^{-1}\left(\frac{SinLatA-(SinLatB.Cosdist)}{CosLatB.Sindist}\right) \tag{3}$$

If the α and β angles have values of less than 90 °, the vertex location is determined between the departure and destination positions. In this case, the latitude of the vertex (Latv) location was calculated as follows:

$$\text{Latv} = \text{Cos}^{-1}(\text{CosA. Sin}\alpha\,) \tag{4}$$

Dlongv refers to the difference between the longitudes of departure and vertex locations.

$$\text{Dlongv} = \text{Cos}^{-1}\left(\frac{TanA}{TanB}\right) \tag{5}$$

DlongVX is the difference between the vertex and waypoint longitude. The latitudes of the waypoint positions are calculated as follows:

$$\text{Lat}x_1 = \text{Tan}^{-1}(\text{CosDlongv}x_1\text{. TanLatv}\,) \tag{6}$$

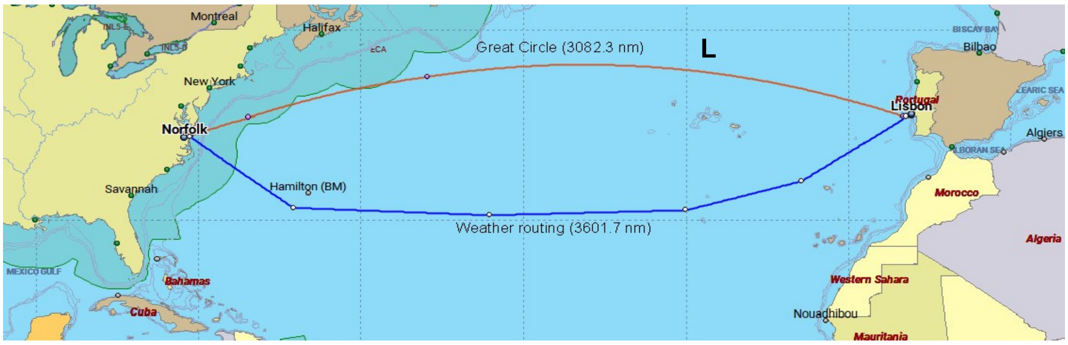
The approach for comparing the GC with WR is explained in Table 1.

Table 1. GC and WR Comparison Algorithm

Step	Steps of the scenario
1	Determination of ports for departure and arrival coordinates.
2	A ship model suitable for ocean passage was selected from a simulation database (NTPRO 4000).
3	Determination of the ocean passage date and time for collecting sea, weather, and current data.
4	Determination of GC and WR courses and calculation of distances using spherical trigonometry equations.
5	Simulating ocean wind, current, and swell conditions in the ocean locations where the computed routes pass.
6	The average speed data were collected by navigating the model ship routes through simulated weather and water conditions.
7	Calculating arrival time and fuel consumption for both scenarios.
8	Comparison and analysis of results.

In this study, Lisbon was selected as the departure port and Norfolk as the destination port as shown in Figure 2. The GC waypoint coordinates were calculated using spherical trigonometry equations by selecting 5° longitudinal differences. The total distance was computed as 3070.31 nautical miles using spherical trigonometry equations. GC arcs can be transferred as divided lines in Mercator projection charts. The distance determined after converting the arcs to lines on the chart was 3082.30 nautical miles. The calculated coordinates were plotted on a Mercator projection navigation chart and the distances and courses between them were identified (Table 3). Tables 4 and 5 were created by collecting data on weather conditions and force in areas where the GC routes crossed the Routeing Chart North Atlantic Ocean (Admiralty 5124) in November.

Figure 2. Great Circle and Weather Routing Courses (Note: This chart is plotted on Netpas Distance



4.1)

Table 2 summarizes the characteristics of the ship selected from the NTPRO 4000 database that sailed on both routes. The expression Maximum Continuous Power (MCR) refers to the power rating of the sustained power output of the ship’s main engine. The environment setting window of the simulator is shown in Figure 3. After generating the environmental variables in the simulator for each route, the ship was left on autopilot control and sailed for 30 minto calculate the average speed.

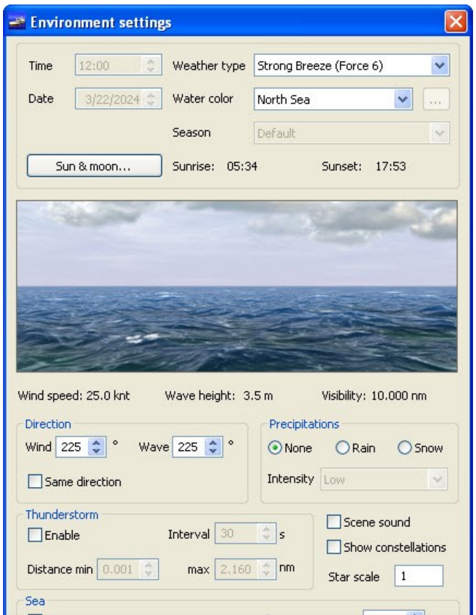


Table 2. The ship model in simulation

Particulars of the ship	
Type	Tanker
Loa [m]	242.8
Breadth [m]	32.2
Deadweight	59708
Full Load Displacement [t] at water densitv 1.025 t/m3	67850
Main Engine Power (kW)	12000
Daily Fuel oil consumption (FOC) [t]	29
Daily Diesel oil consumption (DOC) [t]	2
Laden Speed in knots (85 % MCR)	13.5

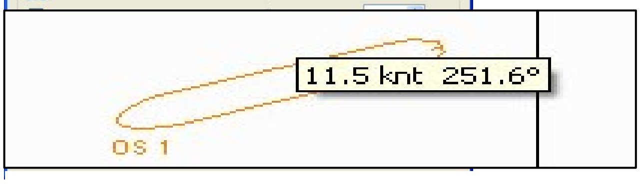


Figure 4. Course and speed data

According to the meteorological data, a gale occurred in the GC route area, followed by November 3 and 15, 2017. A layer of water on the sea surface shifts owing to the wind blowing over it. This surface layer is referred to as the Ekman layer, owing to the deflection generated by the Coriolis force. In the Northern Hemisphere, the Ekman layer is deflected by 40 ° in the open sea and 20 ° to the starboard in coastal waters, instead of the direction of the wind. The drift of the wind-driven current is 2% of the wind speed (Bowditch, 1977). Tables 3 and 4 illustrate the environmental conditions calculated from meteorological data. After the environment was simulated, the average speed of the ship in each course was determined (Figure 4).

Table 3. Environmental conditions along the GC route

WP	**Weather Direction/Beufort**	**Ocean current Set/Drift**	**Wind driven current Set/Drift**	**Significant Wave Height** (m)
Lisboa	N/3	195/0.5	200/0.2	1.0
1	W/5	155/0.5	130/0.4	1.5
2	NW/5	130/0.4	175/0.4	2.0
3	NW/7	130/0.5	175/0.6	3.0
4	NW/8	140/0.4	175/0.8	4.0
5	NW/8	095/0.5	175/0.8	4.0
6	N/7	085/0.5	220/0.6	2.5
7	N/5	085/0.7	220/0.4	1.5
8	N/3	085/0.7	220/0.2	1.0
9	SW/3	090/0.7	085/0.2	0.5
10	SW/5	090/0.7	085/0.4	1.5
11	SW/6	090/0.7	085/0.5	1.5
12	SW/4	060/0.5	085/0.3	1.5
13	W/3	045/0.5	130/0.2	1.0
Norfolk	NW/3	040/1.0	175/0.2	1.0

Table 4. Environmental conditions on WR route

WP	**Weather Direction/Beufort**	**Ocean current Set/Drift**	**Wind driven current Set/Drift**	**Significant Wave Height (m)**
Lisboa	N/3	195/0.5	200/0.2	1.0
1	NE/4	215/0.5	265/0.3	1.5
2	E/3	240/0.4	310/0.2	1.0
3	E/3	280/0.5	310/0.2	1,0
4	NE/3	310/0.5	265/0.2	1.5
Norfolk	NW/3	040/1.0	175/0.2	1.0

The Energy Efficiency Operational Indicator (EEOI) is a metric that evaluates the relationship between the amount of cargo carried by a ship and the amount of fuel used to reduce emissions of greenhouse gases(GHG). EEOI was calculated as follows:

$$EEOI = \frac{\sum_i C_i}{\sum_i T_i . D_i} \tag{7}$$

C_i is the carbon emissions from a voyage. C_i was calculated by multiplying fuel consumption by the carbon conversion factor. The computation should include both the fuel and diesel oil consumption during the voyage. The conversion factors from fuel mass to CO_2 mass were 3.1144 for heavy fuel oil and 3.2060 for diesel oil (IMO, 2009). The fuel consumption values of the ship model were calculated using the daily consumption values of the main and auxiliary engines presented in Table 2. T_i represents the amount of cargo transported in metric tons on a specific Voyage and D_i is the distance sailed in nautical miles while loaded with cargo during a voyage. For both routes assumed that the ship was laden with 58100 tons. After gathering data from the simulated scenarios, the Results and

Discussion section evaluate the effectiveness of the GC Route and WR methods in reducing carbon footprints. Statistical comparisons, such as fuel consumption rates, CO_2 emissions, and arrival times, were conducted between the two scenarios. By critically examining the data and drawing comparisons, this study aims to provide valuable insights into which routing method offers a more environmentally friendly approach, ultimately contributing to ongoing efforts toward sustainable practices within the maritime transportation industry.

3. Results and Discussion

This section provides a complete summary of the quantitative data obtained from the simulations and the subsequent analysis. First, the coordinates of the waypoint positions for the GC, as well as the routes and distances between these positions, were computed using spherical trigonometry equations (Table 5). The steaming time was computed for each route based on the recorded average speeds. The total fuel oil consumption and consumption figures were calculated for each route based on the steaming periods (Tables 5 and 6). The average speed on the GC route was 10.42 knots, however, it was recorded as 13.23 knots on the WR route. According to the data collected, the total steaming time on the GC route was 12 days 7 h 42 min, whereas on the WR route it was 11 days 8 h 07 min.

Table 5. GC route computations

WP	Latitude	Longitude	Course	Dtw	Dtg	Av speed	S.Time	FOC
Lisboa	38°30.00’ N	009° 35.0’ W	288.37	246.14	3082.30	12.9	19.08	23.04
1	39°47.57’ N	014° 35.0’ W	285.18	237.97	2836.16	12.1	19.66	23.74
2	40°49.88’ N	019° 35.0’ W	281.48	231.48	2598.19	12.1	19.13	23.10
3	41°37.72’ N	024° 35.0’ W	278.61	226.70	2366.71	10.2	22.22	26.84
4	42°11.67’ N	029° 35.0’ W	275.27	223.37	2140.01	7.3	30.59	36.95
5	42°32.20’ N	034° 35.0’ W	271.90	221.89	1916.64	6.6	33.61	40.60
6	42°39.57’ N	039° 35.0’ W	268.53	221.86	1694.75	8.6	25.79	31.15
7	42°33.87’ N	044° 35.0’ W	265.16	223.11	1472.89	10.9	20.46	24.71
8	42°15.04’ N	049° 35.0’ W	261.81	226.14	1249.78	12.2	18.53	22.38
9	41°42.83’ N	054° 35.0’ W	258.50	230.79	1023.64	12.4	18.61	22.48
10	40°56.80’ N	059° 35.0’ W	255.23	237.04	792.85	12.1	19.59	23.66
11	39°56.38’ N	064° 35.0’ W	252.04	244.99	555.81	11.3	21.68	26.18
12	38°40.81’ N	069° 35.0’ W	248.93	254.70	310.82	11.5	22.14	26.74
13	37°09.23’ N	074° 35.0’ W	248.32	56.12	0	12.2	4.6	5.55
Norfolk	36° 48.50’ N	075° 40,0’ W	-	-	-	-	-	-
					Sum	10.42	295.69	357.12

WP: Waypoints, Dtg: Distance to go, Dtw: Distance to waypoint, S.Time: Steaming time in hours

Table 6. WR computations

WP	Latitude	Longitude	Course	Dtw	Dtg	Av speed	S.Time	FOC
Lisboa	38°30.00’ N	009° 35.0’ W	237.12	569.15	3601.70	13.4	42.47	51.30
1	33°21.00’ N	019° 23.0’ W	253.84	560.38	3032.55	13.0	43.10	52.06
2	30°45.00’ N	029° 55.0’ W	268.54	939.36	2472.17	13.2	71.16	85.96
3	30°21.00’ N	048° 00.0’ W	272.36	946.42	1532.81	13.6	69.58	84.05
4	31°00.00’ N	066° 14.0’ W	306.46	586.39	0	12.8	45.81	55.33
Norfolk	36°48.50’ N	075° 40,0’ W	-	-	-	-	-	-
					Sum	13.23	272.12	328.70

WP: Waypoints, Dtg: Distance to go, Dtw: Distance to waypoint, S.Time: Steaming time in hours

The arrival time on the WR route, which was 519.4 nautical miles longer than that on the GC route, was calculated to be 23 h and 35 min shorter, respectively. When all FOC data were examined, consumption on the WR route was 28.42 tons lower. The EEOI values for both voyages are calculated as follows:

$$EEOI\ (GC) = \frac{3.1144 * 357.12 + 3.2060 * 24.64}{58100 * 3082.3} = 6.65\ \text{gCO2/ t-nm}$$

$$EEOI\ (WR) = \frac{3.1144 * 328.70 + 3.2060 * 22.67}{58100 * 3601.7} = 5.23\ \text{gCO2/ t-nm}$$

Overall, these quantitative results provide a complete insight into the voyage performance parameters connected with the GC and WR, shedding light on the differences in fuel consumption, steaming times, average speeds, and EEOI. Kobayashi et al. (2015) et al. evaluated FOC and EEOI data on different routes in a scenario they generated for a ship crossing the Pacific Ocean in both directions within a specific time period. Mathematical models were used instead of a class-approved training simulator to estimate ship-sea interactions on different routes. The results of this study, which do not include ocean current and swell information, indicate that the optimized routes are more efficient than the GC route. Pennino et al. (2020) discussed a new adaptive WR model based on the Dijkstra shortest-path algorithm for optimum route assessment. Based on their findings, they concluded that the WR model could lead to significant fuel savings.

4. Conclusion

A voyage optimization strategy based on simulation trials was developed and presented with the aim of planning fuel-efficient voyages. The GC and WR route decisions for the west-bound Atlantic Ocean passage were evaluated in all aspects, with the goal of minimizing EEOI and FOC using weather and sea condition simulations. According to data based on GC and WR voyages, it was determined that the WR route has 21.3% better EEOI than the GC route when comparing the calculated EEOI values. These results indicate that the WR option in the winter Atlantic west-bound passage is more effective in terms of energy efficiency than the GC route in terms of reducing the carbon footprint of marine transportation. Voyage planning is a time-consuming procedure that involves collecting extensive information, performing computations, and performing evaluations. Moreover, when deciding on a voyage route, serious risks such as cargo damage, hull damage, and crew injury from adverse weather conditions should also be considered. The main limitation of this study is that the voyage performance data of a ship in certain weather conditions during a certain period in the Atlantic Ocean were analyzed. The safest and most efficient routes for a ship's ocean passage can be discovered by testing various routes at year-round time intervals. The approach presented in this work seeks to encourage mariner trainers to investigate the links between various navigational methods and other fields of science.

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