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The analysing energy efficiency for sailing ships in optimal travel route planning.
Case study: World voyage of training ship "Mircea"

D Atodiresei[1*], D Coşofreţ[2], A-T. Nedelcu[3], A. Toma[4], C. Popa[5], T. Albayrak[6], M. Perkovic[7]

[1] Ph D. Eng, "Mircea cel Batran" Naval Academy, Constanta, Romania
[2] Ph D. Eng, "Mircea cel Batran" Naval Academy, Constanta, Romania
[3] Ph D. Eng, "Mircea cel Batran" Naval Academy, Constanta, Romania
[4] Ph D. Eng, "Mircea cel Batran" Naval Academy, Constanta, Romania
[5] Ph D. "Mircea cel Batran" Naval Academy, Constanta, Romania
[6] Ph D. ,T. C. Piri Reis Universitesi , Tuzla, Turkey
[7] Ph D. Eng, University of Ljubljana, Slovenia

Abstract: Reducing fuel consumption is a major goal in planning a ship's voyage. In addition to reducing the operational costs of the voyage, this planning objective influences the energy efficiency of the voyage. This study presents a method for identifying the operational energy efficiency in planning a voyage route to sailboats. In this regard, in the first part of the study was developed a method for determining the Energy Efficiency Performance Indicator (EEOI) of a voyage route for sailing ships. In the second part of the study, to validate the developed method, were analyzed two voyage routes, with imposed limitations, to identify the optimal voyage route around the world for the Training ship „Mircea". The Training ship „Mircea" is a training ship for the students of the "Mircea cel Bătrân" Naval Academy. The analysis was performed for two navigation routes, namely from East to West and from West to East, departing/arriving from the port of Constanța. The results of the analysis indicate that the route from West to East is the optimal route for Mircea's voyage around the world from the perspective of the ship's energy efficiency.

Introduction:

Reducing air pollution and in particular greenhouse gas (GHG) emissions is the main global concern for preventing climate change (1). To align the maritime transport sector with these greenhouse gas emission reduction requirements, since 2013, has introduced the International Maritime Organization (IMO) (2) - energy efficiency standards for both ships in the design phase and as well for vessels in operation (3), (4). Thus, the IMO guidelines have required for newly built plan with SEEMP (Ship Energy Efficiency Management Plan) energy efficiency measures and tools to monitor the implementation of these measures during travel, such as EEOI (Energy Efficiency

Operational Indicator) and MRV(monitoring, reporting, and verification of carbon dioxide emissions) (Figure 1) (5) .

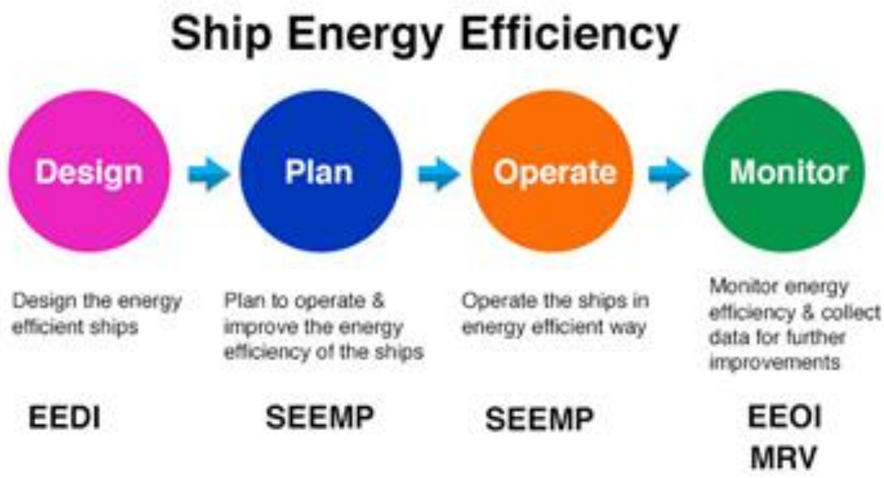

Figure 1. IMO guidelines for increasing Ship Energy Efficiency (5)

The EEOI is an operational measurement tool introduced by the IMO in 2010 that applies to all existing ships which assess measures to reduce CO_2 emissions on board during voyages (6).

Thus, reducing greenhouse gas emissions from shipboard engines and in particular greenhouse gas emissions represent a major objective in the optimal planning of a ship's voyage.

Therefore, the CO_2 emissions produced on board depend on the fuel consumption of the ship's engines (7).

Sail-boats represent the ships (8), which, for propulsion, may use sails, depending on favorable wind conditions. Using sailing propulsion, the propulsion engine is put on rest, therefore the ship's fuel consumption during a voyage decreases in proportion to the period during which the ship will be propelled by sails.

The analysis of the energy efficiency of sailing ships during the a voyage consists, first, in estimating the distances from the voyage in which the ship can be propelled by sails. For this, it is necessary to identify the favourable wind conditions for sailing, based on weather data specific information to different navigation areas and for different periods during the year (9).

The study present the method for analysing the energy efficiency (10) for planning a voyage around the world. The voyage will be executed by Training ship „Mircea", during the period April 2022-February 2023.

The sailing vessel „Mircea" is a training A-class ship, bark type, with three masts, with a height of 44 meters, with 23 mainsails that sum up a total sail surface of 1750 square meters.

To execute the voyage around the world, are proposed and analyzed two different routes, namely: from East to West and from West to East with departure/arrival from/to the port of Constanta.

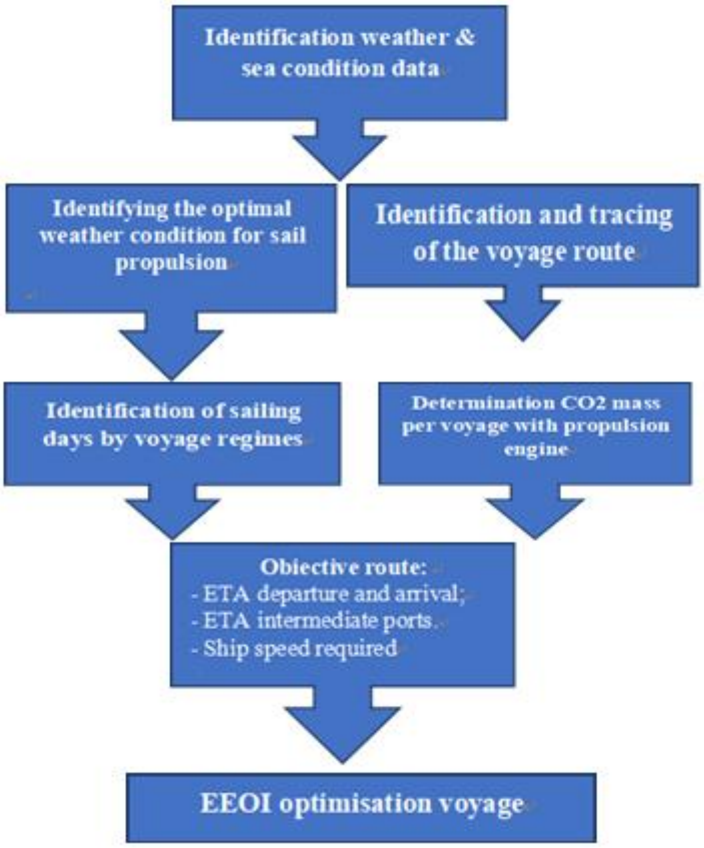

Figure 2. Algoritm for EEOI

1. Research method:

Regarding the analysis of energy efficiency for planning a voyage for a sailing boat, the authors develop an analysis algorithm based on the limitations imposed by the periods of the voyage and the speed imposed for the voyage, an algorithm shown in Figure 2.

1.1. Tracing route

In order to identify the optimal route of voyage, there will be taken into accounts some objectives of the voyage, such as the port of departure and arrival, dates of arrival and stationary in ports of call and departures days, take into consideration the average speed during the voyage (11).

Using the existing dedicated routing software, it is plotted the optimal route of the trip.

Other factors to consider for planning the voyages are: minimum fuel consumption, period of days, minimum distance, safety and security speed, crew etc.

1.2. Weather & sea condition data;

To ensure the safety of ship, it is necessary to take into consideration some weather parameters such as: wind intensity and direction, sea currents, wave intensity and direction. Regarding the sailing ships, the weather conditions also helps us to identify favourable sailing days. Using different sources with information regarding weather statistics, we can determinate the navigation area and the perfect period of voyages.

1.3. EEOI determination

The evaluation of the energy efficiency of a voyage is performed using the Operational Energy Efficiency Indicator (EEOI). EEOI was defined as the ratio of the mass of CO_2 emitted by a ship to a specific unit of work.

During the voyage the ship sails in different regimes (Figure 3), as follows:

- travel regime;
- manoeuvring regime;
- stationary regime.

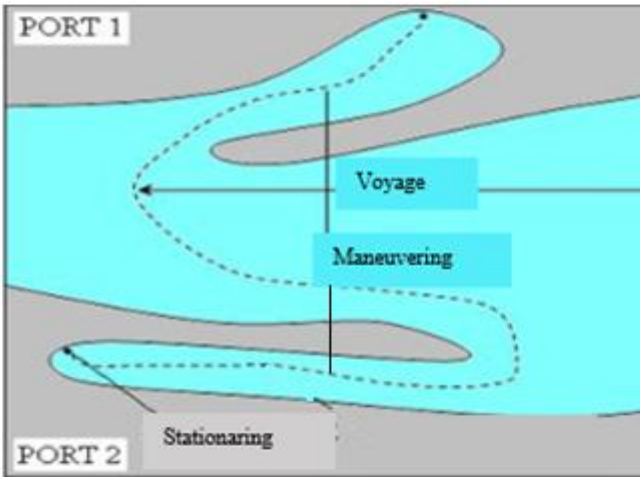

Figure 3. Vessel voyage regimes (4)

The voyage regime of a ship is considered to start at 10 nautical miles from the port of departure and end at 3 nautical miles from the port of entry when the ship begins to slow down to reach maneuvring speed.

In general, the ship manoeuvred in port with low speeds, average between 5 and 8 knots, depending on type of ship.

EEOI is determined using the formula (1):

$$EEOI = \frac{actual\_CO_2\_emission}{performed\_transport\_work} = \frac{mCO_2}{m\_cargo * Di} \quad \text{[tones } CO_2\text{/tonne nautical miles]} \quad (1)$$

where:

actual_ CO_2_ emission- mass of CO_2 emitted by the ship during the voyage

m_{cargo} - weight of cargo carried (tons) on ship

D_i - distance of voyage (nautical miles).

The following formula is used to determine the mass of CO_2 emitted by the ship during the voyage (2)**:**

$$m_{CO2\,ship} = 3{,}666 \cdot c_i \cdot \sum_{ikm} FOC_{ikm} \cdot p_{ikm} \cdot t_{km} + 3{,}666 \cdot c_j \cdot \sum_{jkm} FOC_{jkm} \cdot p_{jkm} \cdot t_{km} \; [CO_2\ tones] \quad (2)$$

where:

$FOC_{ikm} = SFOC_i \cdot P_i \cdot 24 \cdot 10^{-6}$[tones fuel/day] – per hour consumption of propulsion engines;

$FOC_{jkm} = SFOC_j \cdot P_j \cdot 24 \cdot 10^{-6}$[tones fuel/day] - per hour consumption of auxiliary engines;

P_i - propulsion engine power [kW];

P_j - auxiliary engine power [kW];

c_i - the carbon concentration of the fuel that fuels the propulsion engine [%];

c_j - the carbon concentration of the fuel that fuels the auxiliary engine [%];

p_{ikm} - the fraction of the maximum fuel consumption of the propulsion engine in running mode 'm' [%];

p_{jkm} - the fraction of the maximum fuel consumption of the auxiliary engine in running mode 'm' [%];

t_{km} - time travelled by ship for the "m" [days] voyage regime.

Load factor: In the case of propulsion engines, the load factor for the travel speed represents 80% of the MCR (maximum continuous rating). In case of ship's manoeuvring regime, the loading factor can be determined according to the ship's speed, using the formula (3):

$$LF_m = (P_m/P_p) = (v_m/v_n)^3 \quad (3)$$

where:

P_p - propulsion engine power to maximum ship speed [kW];

P_m - propulsion engine power to manoeuvres in port [kW];

v_m - speed of the ship during manoeuvres in ports [knots];

v_n - maximum ship speed [knots]

To estimate the ship's energy efficiency (EEOI) for the voyage routes we developed a program using the Excel Microsoft software. The software can be used for all categories of ships to determine the EEOI Index of a voyage. In program we used the formulas presented above and the following statistical data (12), (4):

Table 4 Specific fuel consumption of naval engines

Ship Age	**Specific consume SFOC (g/kWh)**		
	Slow engine	**Semi-fast engine**	**Fast engine**
Before 1983	205	215	225
1984–2000	185	195	205
After 2001	175	185	195

Table 5. Carbon concentration fuel

Type fuel	Carbon concentration
IFO 380	0,8728
IFO 180	0,861
MDO	0,8683
MGO	0,857
LNG	0,737
B20	0,8396

Table 6. Load factor propulsion engine (PE) and auxiliare engine (AE) depending on the operation regime ship

Type ship	Voyage	Maneuvering	Stationary
Bulk carriers	0,17	0,45	0,1
Container	0,13	0,48	0,19
Passenger ship	0,8	0,8	0,64
General Cargo	0,17	0,45	0,22
Other ships	0,17	0,45	0,22
Tug	0,17	0,45	0,22
RO-RO ship	0,15	0,45	0,26
Refrigerated ship	0,2	0,67	0,32
Ships Tanks	0,24	0,33	0,26

2. Application of the method

The algorithm developed in the study was used to determinate and analyse the energy efficiency for two travel routes around the world for Training ship „Mircea". In both cases, the port of departure and arrival is Constanta Port, Romania.

2.1. Tracing route

To planning the routes, it was used software Navi Planner BVS - Travel planning and route optimization system (13). Using the software, it was created two different routes: one from West to East, and another East to West.

The average speed during the two routes was set at 6 Nd.

The route to the West based on this software is the Black Sea, Marmara Sea, Aegean Sea, Mediterranean Sea, North Atlantic Ocean, South Atlantic Ocean, North Pacific Ocean, Indian Ocean, Red Sea and Suez Canal (Figure 4).

The total distance reached is 29,446 nautical miles, which are estimated to be covered by the ship in 295 days of sailing from the total of 206 days planned. The difference represented the days of stationed in 23 ports.

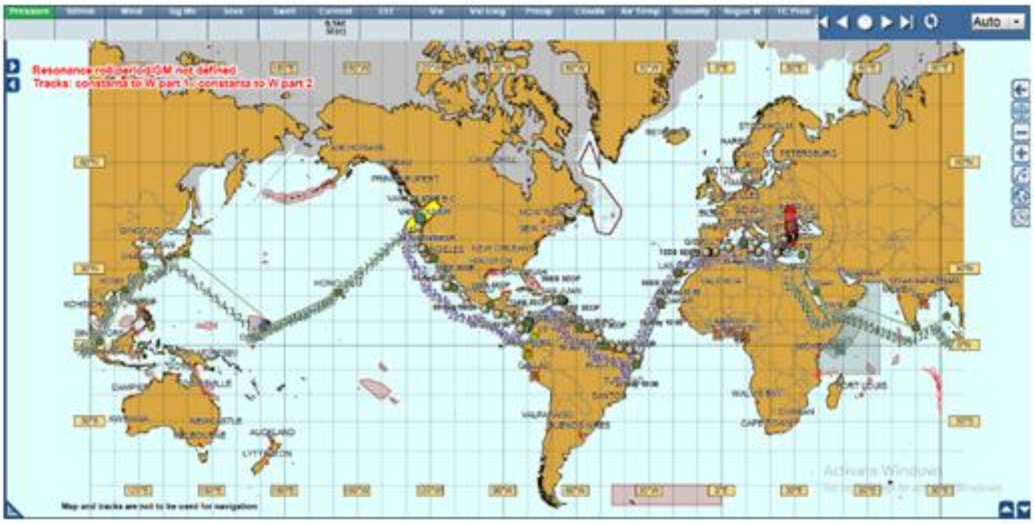

Figure 4. Route to the West modelled with NaviPlanner software (14)

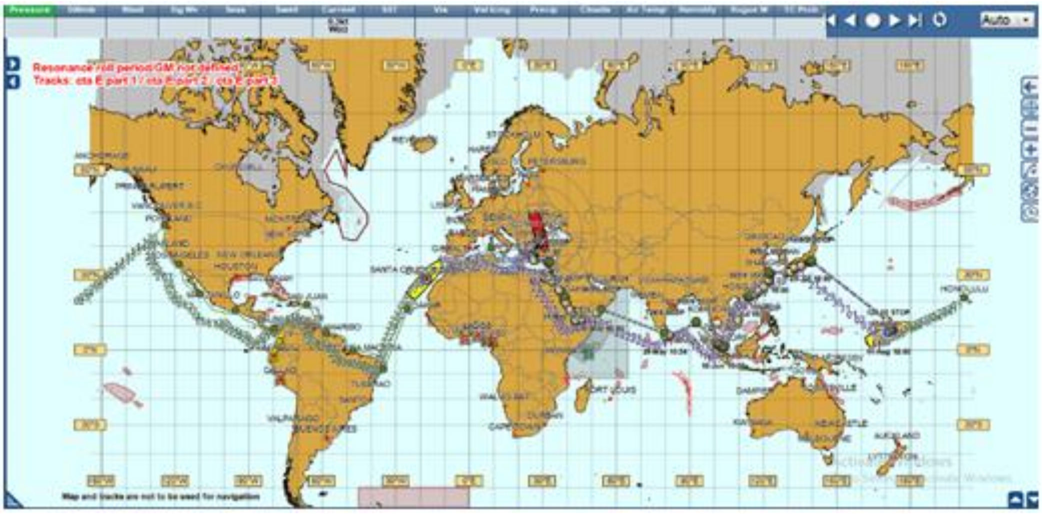

Figure 5. Route to the East modelled with NaviPlanner software (14)

The route to the East is: Black Sea, Marmara Sea, Aegean Sea, Mediterranean Sea, Suez Canal, Red Sea, Indian Ocean, North Pacific Ocean, South Atlantic Ocean, North Atlantic Ocean (Figure 5). The total distance travel is 29,679 nautical miles in the 206 days of the voyage. Therefore, it can be seen that we have the same days of travel and the same days of stationing in the 23 ports of call, the difference is represented by the distance.

2.2. Weather & sea condition data;

Regarding planning a voyage the identification of weather conditions (wind intensity and direction, sea currents, wave intensity and direction) it is necessary to ensure the safety of the ship during its development. In case of sailing ships, knowing the weather conditions also helps us to identify favorable sailing days with favourable winds. To identify the weather conditions we can use and acces different sources with weather statistics depending on the navigation areas and the period of voyage. For the voyage of the Training ship „Mircea”, the analysis of the climatic conditions of the two routes was carried out using SPOS ship performance optimization program (17). The analysis of both routes was performed on the areas related by the months of travel, taking into account five parameters (wind, waves, currents, air temperature and water temperature). Figure 6 shows the SPOS software interface.

Figure 6. Example of the forecast for January through the SPOS software (17)

For a better analysis of the main point of interest in this study, exactly sailing, we analyzed from the 412 days of both routes, the movement direction of the ship, the wind direction from which he blows, and its strength. The data was processed using the Matlab program (15) which showed the following graphs (Figure 7-9). In Figure 7, for the West and Figure 8, for the East, with the red line is represented the force of the wind, as well as its average on the whole voyage with the value of 7.3 m/s, respectively 6.5 m/s, and at the bottom of the graph, it is drawn with blue line favourable or unfavourable sailing wind.

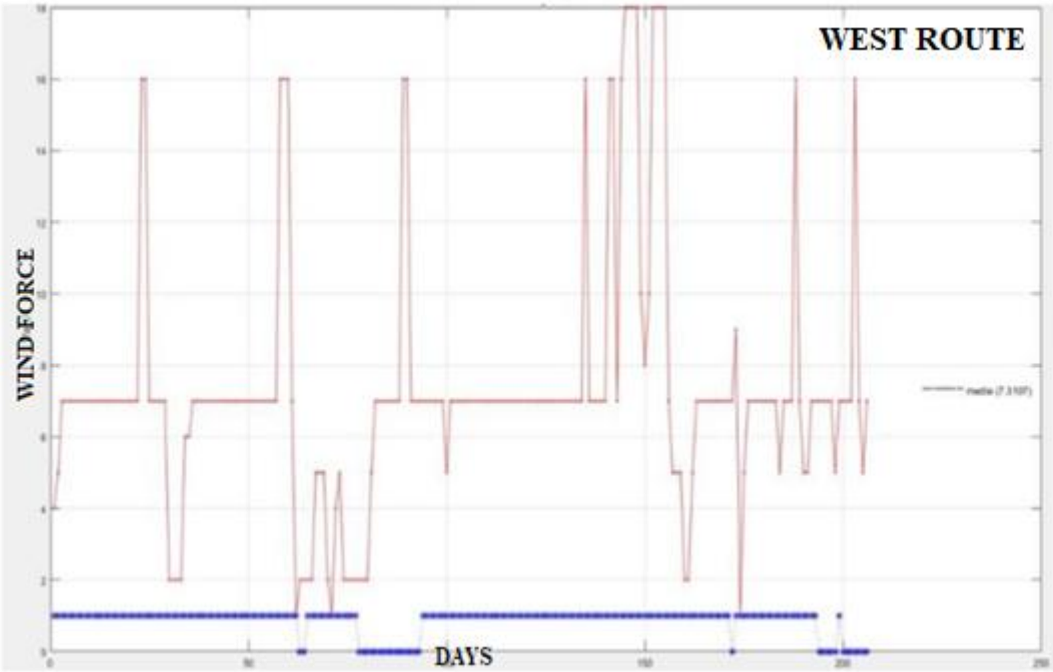

Figure 7. Analysis on favourable days sailing, voyage to the West (favourable wind is the one represented in blue above the abscissa, and the unfavourable one on the abscissa)

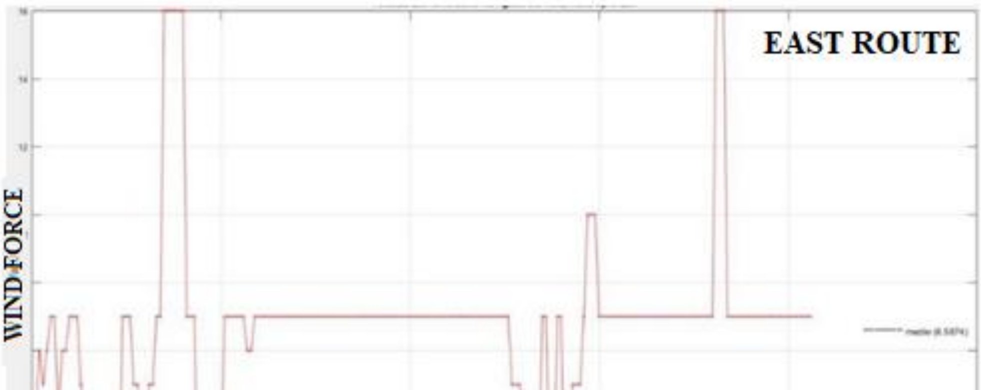

Figure 8. Analysis on favourable days sailing, trip to the East (favourable wind is the one represented in blue above the abscissa, and the unfavourable one on the abscissa)

In Figure 9 is presented a comparison of favourable or unfavourable winds on both routes, during 206 days of voyages. The blue color is assigned to the route to the West and the red color to the route to the East. At the top are represented the days with favourable wind and at the bottom the days with unfavourable wind sailing.

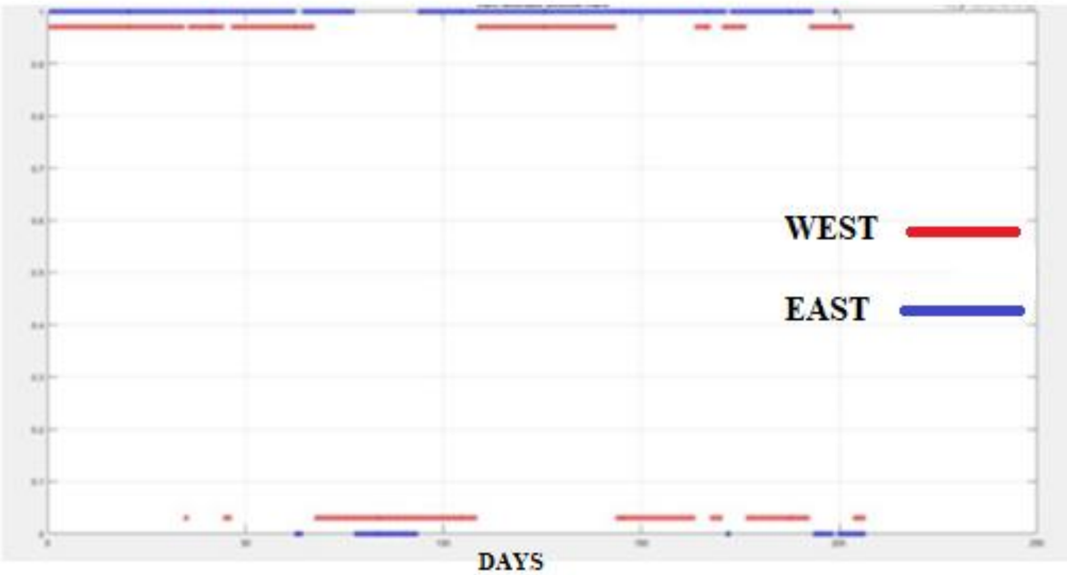

Figure 9. Comparative wind direction for West/East route

Following the analysis performed in the SPOS program, which included the analysis of five hydro-meteorological parameters, it appears that the wind is favourable for sailing during the route to the West, the waves are not very high, in order to create problems, the currents have values of maximum 0.9 m/s significantly influences the direction and speed of advance (16), and air and water temperatures do not create discomfort on any of the routes.

Table 7. Route to the West

Month	West Route	Wind	The number of days of sailing
1.	Constanta - Cagliari	6m/s NE, W	5
2.	Cagliari -Santa Cruz	8 m/s NNE, SE	7
3.	Recife - Colon	7m/s ESE	8
4.	Colon - Cabo San Lucas	2m/s SW, SE	8
5.	Tokyo -Honolulu	7m/s NW, NE	8
6.	Honolulu - Los Angeles	7m/s NE	5
7.	Los Angeles - Salina Cruz	7m/s E,SE, NE	5
8.	Salina Cruz -Belem	7m/s NW, NE	10
9.	Belem - Porto Grande	6m/s NE	5
10.	Porto Grande - Constanta	7m/s NW,NE	7
Total days of voyage by sailing			**68**

Table 8. Route to the East

Month	East Route	Wind	The number of days of sailing
1.	Constanta - Jeddah	4m/s, NE,NV	7
2.	Jeddah - Colombo	4m/s, SV	6
3.	Colombo - Hong Kong	5 m/s, SV	7
4.	Hong Kong - Tokyo	7m/s, SSV	7
5.	Tokyo -Honolulu	7m/s, SE	5
6.	Honolulu - Los Angeles	7m/s, NE,NV	5
7.	Los Angeles- Salina cruz	5m/s, NE	5
8.	Salina Cruz -Belem	7m/s, NE,SV	5
9.	Belem - Porto Grande	7m/s, SE,NE	5
10.	Porto Grande - Constanta	7m/s, NE,NV	7
Total days of voyage by sailing			**59**

Data presented in Tables 7 and 8 represent the analysis of data collected using the SPOS software (17), regarding the wind direction and force for each route of the two analysed routes resulted from the number of days in which the wind direction and force are favourable for sailing.

It can be deduced from the analysis that, in the case of the route to the West, the ship can sail for 68 days, and in the case of route to the East, the number of days of sailing are 59.

2.3. EEOI determination

To determine the energy efficiency in both cases of Training ship "Mircea", was develop an Excel interface program calculation presented in Table 9 and Table 10.

Table 9. Input data for route to East

The type of ship	Other ships
The age of the ship	Before 1983
Ship speed	6
The type propulsion engine (PE)	Semi-fast engine
The type of ship	Other ships
The age of the ship	Before 1983
Ship speed	6
The type propulsion engine (PE)	Semi-fast engine
Number propulsion engine (PE)	1
Power PE [Kw]	808
Fuel type PE	MDO
Diesel-generator type	Semi-fast engine
Number diesel-generators	3
Power diesel-generator[Kw]	107
Fuel type Diesel-generator	MGO
Days of travel	206
Exit maneuver days	10
Entrance maneuver days	10
Days of stay in ports	89
Days of sailing	59
DWT	681

Table 10. Input data for route to West

The type of ship	Other ships
The age of the ship	Before 1983
Ship speed	6
The type propulsion engine (PE)	Semi-fast engine
Number propulsion engine (PE)	1
Power PE [Kw]	808
Fuel type PE	MDO
Diesel-generator type	Semi-fast engine
Number diesel-generators	3
Power diesel-generator[Kw]	107
Fuel type Diesel-generator	MGO
Days of travel	206
Exit maneuver days	10
Entrance maneuver days	10
Days of stay in ports	89
Days of sailing	68
DWT	681

The results obtained by applying the software for the two analysed routes are presented in Tables 11 and Table 12.

Table 11. EEOI East route

RESULT	**Amount of CO_2 (t) in voyage**	**Amount of CO_2 (t) at the maneuver**	**Amount CO_2 (t) in stay in port**	**Amount of CO_2 (t) travel total**	**Reduced amount of CO_2 (t) by sailing**	**EEOI**
Other ships	1.690,785489	25,764	10,18921448	1726,738	626,420	0,0000861

Table 12. EEOI West route

RESULT	**Amount of CO_2 (t) in voyage**	**Amount of CO_2 (t) at the maneuver**	**Amount CO_2 (t) in stay in port**	**Amount of CO_2 (t) travel total**	**Reduced amount of CO_2 (t) by sailing**	**EEOI**
Other ships	1.587,268010	25,764	10,18921448	1623,221	721,975	0,0000809

Analyzing the results obtained for both routes around the world, it is concluded and observed that the route from West to East has a lower EEOI index than the route from East to West, the reduction of CO_2 emissions being about 100 tons. In the case of the East route, the amount of CO_2 travel total is 1726.738 t CO_2, and in the case of the West route the amount of CO_2 travel total is 1623.221 t CO_2.

3. Conclusion

In general, identifying an optimal route for voyages involves a multi-factor analysis. The main factors that must be taken into consideration are the safety of the ship and its crew, the operating costs, and, last but not lEast, the impact of the ship on the environment during the voyage. This article has developed a method of analyzing a voyage route for sailing ships from the perspective of reducing the impact of air pollution with CO_2 emissions on-board engines (18). This method can be applied to all categories of ships using the software developed and presented in the article.

To validate the method, it was chosen to apply it in order to identify an optimal travel route of ships around the world, analyzing two proposed routes, namely, one from East to West and one from West to East with departure /arrival in /from the port Constanța.

The results obtained after analyzing all the factors in the study, the optimal route of the ship for a voyage around the world is the route that departs in the spring season (April) from the port of Constanța, heading West.

In conclusion, the method of energy efficiency analysis onboard sailboats developed, presents a perspective of reducing CO_2 emissions in the analysis to identify the optimal voyage of a sailboat, with applicability for other categories of ships (19). Also, the Excel program created can be used for all types of ships, as the database includes all ships (according to Table 4-6).

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