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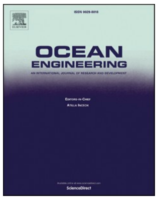

A new strategic approach of energy management onboard ships supported by exergy and economic criteria: A case study of a cargo ship

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ABSTRACT

The fossil-source energy consumption in maritime transportation is an important input which affects the operating costs. In this market, cargo ships with potentially represents up to 78% of the total global maritime transportation are considered as vessels with a high fossil fuel consumption. These ships need effective energy management to reduce environmental pollution from fossil fuel and to manage sustainable energy-related costs in commerce. In this study, an energy efficiency strategy framework was developed primarily to support efficient energy management as the decision support element in ships. Considering the ship's cruising processes, energy efficiency and economic effectiveness were examined as based on the exergy approach and the economic criteria. In this context, two new criteria were developed: the "Environmental Cost Index (ECI)" and the "Energy Efficiency Index (EEI)". According to the analyzes results, the energy and exergy efficiencies in the sample ship's cruising processes were found as 38.33% and 35.82% respectively, and the calculated ECI was 0.41. These reference values showed that the fuel-related loss cost of the ship was 19.05%. At the end of the study, some evaluations were made on the implementation of the energy efficiency strategy and its effects.

1. Introduction

Although having a low capacity to struggle with global warming and climate change, maritime shipping, which covers about 90% of world transport, is an exceptional sector which is showing important developments. In this sector, where the bulk carrier transportation rate reaches approximately 78% of the total commodity transportation in the world, "energy consumption does not only have an environmental impact but also has increasing economic costs".

From this perspective, while developing solutions for this problem, all of the actors' primary strategy must be based on an energy efficiency approach. But, first of all, this effect must be described individualistically on the basis of energy consumption. In this context, the International Maritime Organization (IMO) carries out comprehensive studies to reduce the increasing emission effect like Energy Efficiency Design Index (EEDI) and Ship Energy Efficiency Management Plan (SEEMP). In particular, researches, communiqués and studies based on technical, operational and design measures, as well as effective energy management processes and reductions of greenhouse gas emissions, which can be implemented in existing ships, are being continually carried out (Ferreira and Kirk, 2012).

The shipping industry has a significant environmental impact, cross-border nature, and slow progress in reaching environmental and social sustainability aims (Schwanen, 2015). Shipping is the only sector in the EU where greenhouse gas emissions have risen since 1990, and in particular, the respective shares of emitted air pollutants coming from long-distance air and maritime transport are growing (EP, 2015). Although having a highly competitive atmosphere, the shipping industry has low cooperation among stakeholders. From an environmental protection point of view, governments' and the shipping industry's interests are not fully matched. Despite increasing regulatory efforts to promote "green" or "clean" shipping, environmental governance of shipping has been fragmented. Lack of necessary coordination and harmonization in international arena creates some uncertainties in establishing statutory compliance requirements and standards (Lister et al., 2015; Yliskylä-Peuralahti and Gritsenko, 2014). In addition, shipping is a cross-border activity that brings forward the aspects of place-bound and multi-scalar nature of sustainability governance. Shipping is regulated by complex multi-level governance arrangements

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Abbreviations: ANN, Artificial Neural Network: ECI; Environmental Cost Index: EEI, Energy Efficiency Index: EEDI; Energy Efficiency Design Index: EEOI, Energy Efficiency Operational Index: GDP; Gross Domestic Product: IMO, International Maritime Organization: OECD; Organization for Economic Co-operation and Development: SEEMP, Ship Energy Efficiency Management Plan.

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Nomenclature

Symbols

E	energy rate (kW)
$\dot{EX}$	exergy rate (kW)
h	specific enthalpy (kJ/kg)
I	irreversibility rate, exergy consumption rate (kW)
IP	improvement potential rate for exergy (kW)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (Pa)
Q	heat transfer rate (kW)
s	specific entropy (kJ/kgK)
Ś	entropy rate (kW)
T	temperature (K)
$\dot{W}$	work rate or power (kW)

Greek Letters

Ŋ	energy(first law) and exergy efficiency (second law) (%)
Ψ	flow exergy (kJ/kg)

Indices

k	kinetic
ph	physical
ch	chemical
pt	potential
dest	destruction
gen	generation
in	input
0	dead state or reference environment
00	partial
out	outlet

present in different regions (Roe, 2013; Schwanen, 2015). Any efforts to make shipping more sustainable need to take into account formal governance institutions and mechanisms, and also informal institutions, such as “political practices, social networks and norms” that reproduce and maintain present practices in shipping (Gibbs, 2006). Although all of these approaches are defined as an obligation of direct sectoral development, they should be considered within the scope of the efficient use of energy and the effectiveness of energy management.

However, energy management in sectoral sustainability has a versatile and complex structure. Ship voyage processes, which are the main focus of consumption, include optimal techniques. For example, Zaccone et al. (2018) developed a dynamic programming method and aimed at efficient fuel consumption in the process. Yana et al. (2018) established an energy efficient model based on environmental factor by using big data for ships. This model aims to divide the route along with environmental criteria. Yasser and Ölçer (2020) improved fuel consumption estimation with Artificial Neural Network (ANN) and Multi Regression Approach and stated that this approach is compatible with the changes.

The world seaborne transport is expected to increase by 4% yearly in the commodity by 2050, indicating that sectoral greenhouse gas potential will increase about 3 times. In this framework, intensive studies are being conducted on alternatives for possible mitigation of the sector with about 3–4% of total greenhouse gas emissions (James and James, 2008; Stopford, 2009). It has been observed that the fuel consumption of fossil fuels, especially diesel consumption, has a significant effect in this process. For this reason, IMO defined precautionary restrictions in three stages for reduction of environmental threats (Tadros et al., 2019; IMO, 2016a,b). In this context, energy efficiency and energy saving can be seen the main criteria for the reduction of emissions based on fossil energy consumption for ship management. All of these evaluations have shown that to establish a plan or strategy about sustainability savings on energy efficiency for ship management is a necessity. Developed along these lines, this study presents an approach to energy efficiency strategy that will support efficient energy management processes based on the energy efficiency of ships. In this study, in the defined voyage processes of vessels, effective efficiency evaluations, emission effects and related economic performance processes are examined. This paper intends to achieve three major goals:

1. Explaining the importance of sustainable indicators of the ships, which covers not only energy efficiency but also the economic sustainability that are relevant to the ship routes.
2. Analysing the effectiveness of ships’ energy efficiency practices through sustainable indicators.
3. Helping marine companies to develop and/or adopt their energy efficiency policies for ship management.

2. Maritime shipping and energy management

The maritime transportation, which became a major player in the global economy after the 1944 Bretton Woods agreement and strengthened its position today, is a complex structure that not only covers interregional transport (deep-sea shipping), but also many activities such as short sea shipping, inland transport, which includes road, rail, river and canal transport and passenger transportation (Stopford, 2009). In international trade, commodity (freight) transportation, including liquid and dry bulk, containerized and specialized shipping, has increased by 5 times since the 1970s. The freight market has had a remarkable effect on maritime transportation. Maritime Shipping is a useful tool to improve the capabilities of the ports and helps the economy of the cities. Economic activities directly related to the oceans are gradually increasing in the world. Maritime activities significantly contribute to the total Gross Domestic Product (GDP)’s of countries and are vital for global development.

In international processes, GDP and fuel sold for international maritime transport are two important criteria. According to these two criteria, considered over the past 20 years, Organization for Economic Co-operation and Development (OECD) countries have taken into account a volume that has increased from $ 20,000 to $ 40,000 in GDP and capacity that doubled in Mton consumption during the same period (James and James, 2008). In spite of the growth in commercial volume, the processes brought by international competition showed that effective cost management is an important process in the sector. In this process brought about by international competition, studies based on reducing input costs in enterprises necessitate effective energy management first.

Increasing competition in maritime shipping affects direct costs and forces businesses to take additional measures in terms of efficiency. Shipping costs have risen by about 60% in some instances and, fuel costs are a key component of this and need to be specifically assessed. The development of strategies based on energy efficiency and efficient use of energy as a management strategy, especially in ships, will directly affect energy consumption per commodity/ton carried (Insel, 2012). Currently, the percentage of fuel costs for cargo ships in total operating costs is around 70%, while they consume about 4% of total fossil fuel of the world (Boardley, 2014). In this respect, sustainable energy management processes must be considered together with power management strategies in ship operation. Power management of vessels is fuel-bound management and depends on external factors, technical efficiencies and efficiency of operation maintenance processes. The energy management system approach that started with ISO 50001 has contributed to many sectors in this respect. With EEDI and SEEMP, IMO has led the maritime industry. But the most important process is the development of a management strategy that will develop them in ship operation (Ferreira and Thomas, 2012; Gilbert et al., 2010). Although the EEDI is actually considered as a valid criterion by IMO and national maritime enterprises, it is not defined as a condition for all vessels. The EEDI, defined by the evaluation of the environmental impact of a ship based on social benefit, is an indicator developed mainly for new ships rather than being an indicator for existing ships. In other words, the machine power, which is planned at the design stage of the ship machinery and installed as the system of the ship, is shaped as a result of an improved correlation between the speed and load of the ship. Energy Efficiency Design Index is calculated by the "EEDI = (Power.SFC. FC)/(Deadweight.Speed)" formula. The effect of cargo and speed of ships are directly effective parameters on fuel consumption. However, an energy performance criterion according to these criteria does not provide sufficient infrastructure for a sustainable management model (Lützen, 2017).

SEEMP can be seen as an improved management plan onboard ships. It has a structure that will improve the effective management processes of energy like ISO 50001 by considering the current operating conditions onboard ships (Jensen, 2018). However, if a management strategy is not developed for these structures, these plans only develop a process in which the possible conditions are monitored and evaluated.

For this reason, there is a need for the holistic development of energy management for sustainable effect in system performances. For example, Hongtao et al. developed a framework for the "Real-Time Energy Efficiency Operating Index" for defining real fuel consumption and related carbon dioxide emission data reported by individual ships (Chi et al., 2012). Structural models that will improve the energy efficiency of ships are the most common applications nowadays. For example, Santiago et al. investigated the heat recovery process by using Organic Rankine Cycle (ORC) (Santiago et al., 2017). These type of applications can be defined as improvement actions in energy management processes considering energy performance. But, these steps must be consistent with strategic approaches which are developed in this study.

3. Energy efficiency strategy for ships

There are important opportunities based on efficient energy use which will require the efficient management of energy in ships which are the main elements of maritime transport. There is a need for efficient energy management for the energy efficient operation of engine and substructure components for ships. With the help of efficient energy management elements to be developed within this scope, the creation and use of sectoral demand for efficient technologies will reduce energy-related costs in sectoral competition. As a matter of fact, Konstantinos-Marios and Gerasimos (2018) developed a systematic energy management methodology for the ship propulsion engine.. In this study, the developed methodology is based on an improved statistical analysis structure based on the operating conditions of the motor with many input parameters. Marie et al. created a framework for energy efficient operations on ships for decision support elements (Jensen, 2018). The frame is defined by three models. The first model refers to the state of the operational modes of the ship, the second model is based on conceptual dependence on the processes, and the third model is their integrated solution processes. Another study about optimization procedure to minimize fuel consumption of a four-stroke marine turbocharged diesel engine was developed by Tadros et al. (2019). They developed a numerical optimization model for simulation of a large four-stroke marine turbocharged diesel engine and defined some optimal values for some parameters like the speed of the turbocharger, start angle of injection and amount of injected fuel. Tran proposed operational energy efficiency optimization approach with the multi criteria decision making approach. He especially evaluated the impact parameters in navigational conditions (Tran, 2020). All of these studies have shown that energy management should be considered primarily in system integrity. However, all processes with a commercial value on ships are primarily based on decreasing energy consumption and reducing cost effects. Energy management is a process of managerial organization in direct or indirect energy consumption of all vehicles in service and production. In this context, the main purpose of an energy management system onboard ships should aim at reducing energy consumption and costs in the first place as defined in Fig. 1.

As with all energy consuming processes, many reasons prevent the realization of the defined targets in ships. Many preventive studies have also been developed for these barriers that energy management faced. For example, Hannes Johnson, in his case studies, investigated the obstacles related to energy efficiency in short sea shipping by an Action Research Method (Johnson, 2019). In another study, especially in problems relating to ship - shore communication, sharing of responsibilities and performance problems are seen as important points (Lützen, 2017).

EEDI and SEEMP developed by the IMO are used as the management and control procedure for evaluation of ship energy efficiency and management applications. But, SEEMP was developed especially from ISO 14000 and it is not sufficient enough for development strategies related to energy efficiency when considered ship energy consumption processes. For example, in ISO 50001, requirements are imperative but not in SEEMP. In addition, while Goal Setting in ISO 50001 is a basic behavior, it is a volunteer action in SEEMP. Johnson made a comparative evaluation regarding the differences in both plans in this study, as given in Table 1.

Therefore, a decision support element is needed for efficient management of energy in the ships' management program. In this context, in order to be able to successfully implement these IMO legislations for ships, the energy efficiency strategy has been developed with a flow diagram in Fig. 2.

There are five main stages in strategy development related to management processes. In these management processes developed for energy management, strategic management elements were evaluated. A database must be created for each ship in transportation sector. In the analysis of the data to be generated, the energy efficiency analyzes of the ship for defined route management and the energy and exergy efficiencies of each process should be monitored continuously with a dynamic program. In this process management, target efficiencies should be developed by defining the baseline. In terms of decision processes, this should be defined separately for each energy consumption element. In these potentials, the economic parameters of the management tools and action plans should also be shaped depending on the target and consumption behaviors created in the process.

For cargo ships, it is possible to develop many actions directly or indirectly in all components (such as for main engines, motors, heat exchangers, connected systems and operating parameters). Significant savings are achieved, for example by following an action based on air to fuel rate (fuel consumption reaches a minimum as air to fuel ratio reaches 14.5: 1 for diesel fuel). The process which can be done without investing can be the control of air-fuel ratio optimization. Fuel efficiency can be improved by increasing the combustion efficiency depending on the power curve followed in the ship engines. Load effect and heat rejection rate parameters are also effective on thermal efficiency of the engine (MAN, 2009; Al-Shemmeri, 2011). These actions should be monitored with business management models and target analyzes should be evaluated. The completed process should be turned into a management tool as a decision support element with its results. This strategic management process will contribute to the development of a behavioral culture that will sustain energy efficiency onboard ships. It will also improve the management of parametric values, especially for EEDI. Energy efficiency in ships should also be considered in terms of sustainability. In this context, economic criteria have been developed to evaluate the environmental impact with the economic dimension. These criteria have been developed to enable maritime companies managers to assess the impact of gains that can be achieved through energy efficiency. Economic criteria can be expressed as a decision support

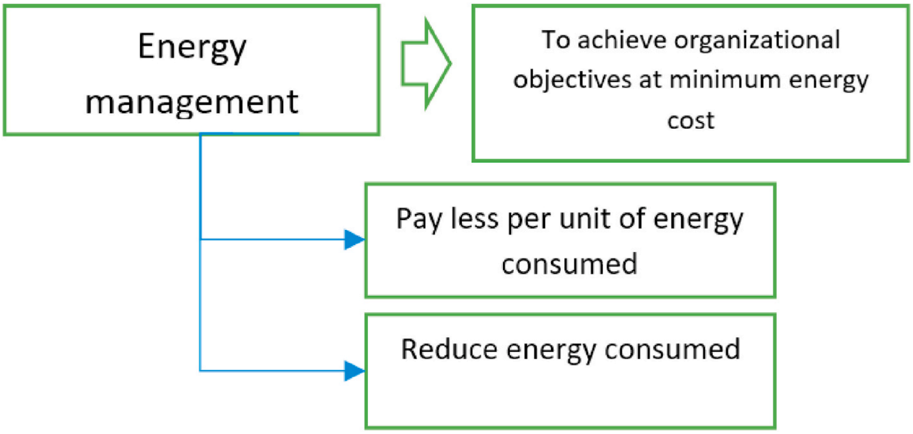


Fig. 1. Aim of energy management (IMO, 2016b).

Table 1
Comparison between the SEEMP and ISO 50001 (Johnson, 2013).

No	Requirements	SEEMP	ISO 50001
1	Top management responsibilities	Missing	Required
2	Management representative	Missing	
3	Policy	Mentioned	
4	Energy review and baseline	Mentioned	
5	Plans, goals and indicators	Mentioned	
6	Implementation and responsibilities	Required	
7	Competence and training	Mentioned	
8	Communication	Mentioned	
9	Documentation	Required	
10	Design and procurement	Missing	
11	Operational control	Missing	
12	Monitoring, measurement and analysis	Required	
13	Internal audit	Required	
14	Nonconformities	Missing	
15	Management review	Missing	
16	Shipping-specific measures	Mentioned	

measure for the energy efficiency strategic approach.

4. Theoretical analysis

Ship engines are mostly diesel engines and are referred to as thermodynamic heat engines in their operation processes. They are operated on a cycle basis as systems with combustion and associated energy transformations. However, power requirements in operation processes depend on the effect of fuel energy consumed in the cycle. For continuous flow conditions, the relationship between the fuel delivered into the system and the resulting product is expressed by a mass balance that is directly connected to the flow of the incoming and outgoing material ($\dot{m}_{in}$; $\dot{m}_{out}$);

$$\dot{m}_{in} = \dot{m}_{out} \tag{1}$$

The first law of thermodynamics defines the overall energy balance for the work and heat produced and, depending on the principle of conservation of energy under such cycle conditions. The overall energy balance for this cycle can be written as the following;

$$\sum \dot{E}_{in} = \sum \dot{E}_{out} \tag{2}$$

$$\dot{Q} - \dot{W} + \sum \dot{E}_{in} - \sum \dot{E}_{out} = 0 \tag{3}$$

$$\dot{Q}_{net} - \dot{W}_{net} = \dot{m}_{out}\left(h + \frac{V^2}{2} + gz\right)_{out} - \dot{m}_{in}\left(h + \frac{V^2}{2} + gz\right)_{in} \tag{4}$$

In the above mentioned equations, the total input and output flow of energy are indicated by $\dot{E}$ and in equation (4); the net heat flow in the cycle is indicated by $\dot{Q}_{net}$ and the net work amount is indicated by $\dot{W}_{net}$ whereas "$h + \frac{V^2}{2} + gz$" defines enthalpy, kinetic and potential effect, respectively. All cycles produce work or heat within the surrounding temperature (Cengel and Boles, 2018). Therefore, the conditions under which they exist affect system efficiency. This process, stated by the concept of Exergy, defines the maximum work that can be done for the dead state conditions according to the second law of thermodynamics. General exergy rate for each point of flow can be expressed as (Szargut, 1986);

$$\dot{E}_x = \dot{E}_{ph} + \dot{E}_{pch} + \dot{E}_{kin} + \dot{E}_{pot} \tag{5}$$

Here, in this equation $\dot{E}_{ph}$ is physical exergy, $\dot{E}x_{ch}$ is chemical exergy, $\dot{E}x_{kin}$ is kinetic exergy and $\dot{E}x_{pot}$ is potential exergy. The overall exergy balance in the cycle for continuous flow conditions may be expressed as;

$$\dot{E}x_{in} = \dot{E}x_{out} \tag{6}$$

$\dot{E}x$ defines the total exergy flows input and output for the system boundiuries. If the potential, kinetic and chemical exergy are neglected, the exergy flow is directly related to the physical exergy flow and the equation of $\dot{E}x_{in} = \dot{E}x_{out}$ can be written as;

$$\phi = (h_i - h_0) - T_0(s_i - s_0) \tag{7}$$

Here, "ϕ" is the flow of exergy, "s" is entropy, index "$_0$" refers to the environment in the dead-state (P_0 and T_0) conditions(Dincer and Rosen, 2012). The exergy balance of combustion processes during the flow process is defined directly by chemical exergy. This connection is related to partial pressure conditions. Chemical exergy in these conditions is defined as below.

$$\dot{E}_{ch} = \dot{m}RT_0 \ln\frac{P_0}{P_{00}} \tag{8}$$

Where R represents the gas constant, P_0 and P_{00} respectively define the medium and partial pressures of the system. However, in general system approaches, the exergy of the fuel is directly based on the exergy factor of the fuel. Chemical exergy in these conditions is;

$$\psi^0_{Cf.f} = \omega.(NCV)^0 \tag{9}$$

In this equation, ω is the factor of standard specific chemical exergy of fuel and NCV *is* the net calorific value of the fuel (Kaushik and Omendra, 2013). As a thermal process, the overall efficiency of the cycle can be calculated depending on both the first and second laws of thermodynamics. In these conditions, the basic equality is evaluated according to the energy or exergy flows between the output and the input (Moran et al., 2011). Accordingly, the general equations of the efficiency are as follows.

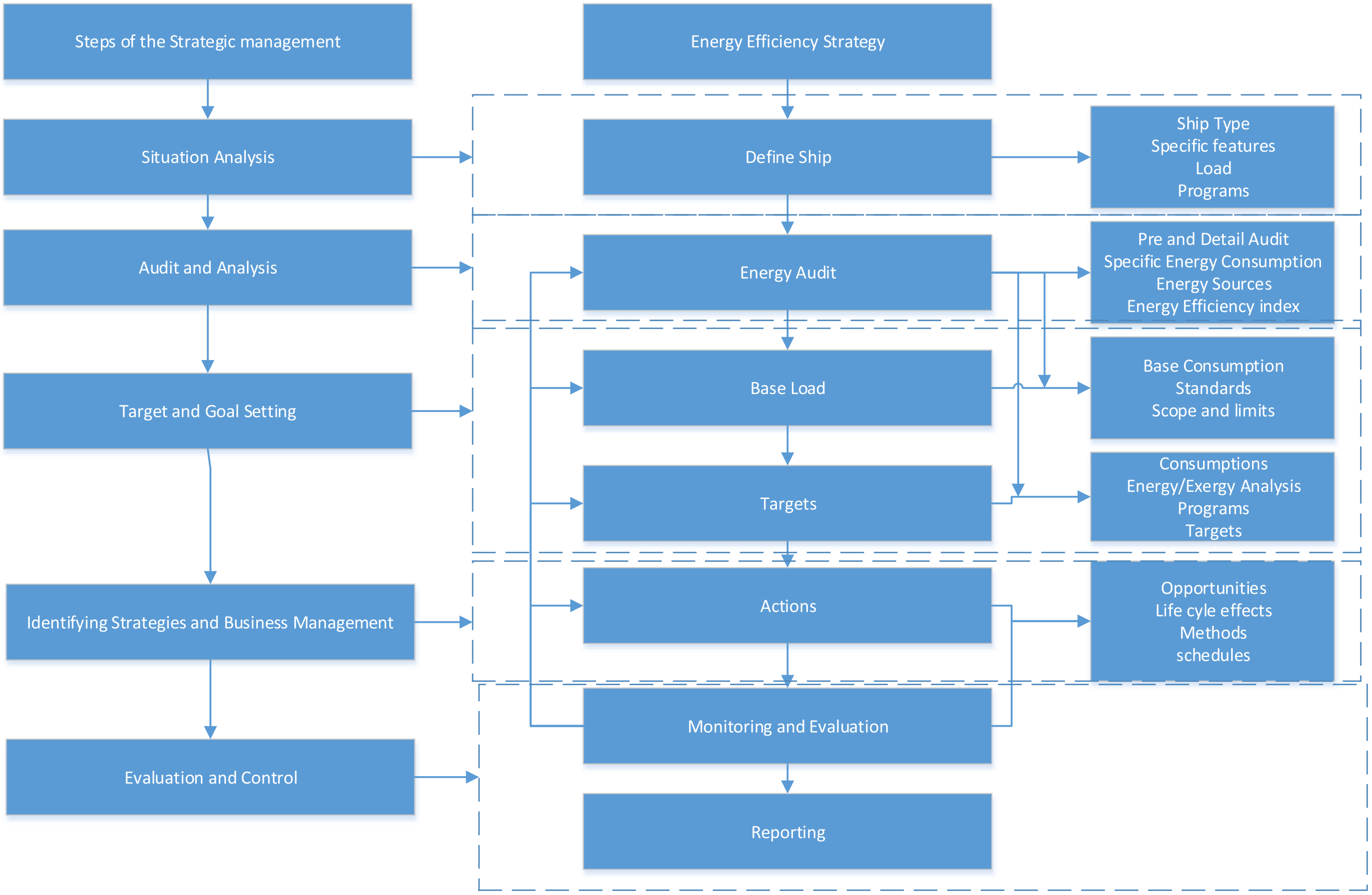


Fig. 2. Flow diagram of energy efficiency strategy.

$$\eta_I = \frac{\dot{W}_{net}}{\dot{E}_{in}} = 1 - \frac{\dot{E}_{out}}{\dot{E}_{in}} \tag{10}$$

$$\eta_{II} = \frac{\dot{E}x_{out}}{\dot{E}x_{in}} = 1 - \frac{\dot{E}x_{dest}}{\dot{E}x_{in}} \tag{11}$$

Where, E is the energy flow for input and output, η is efficiency by indis "*ι*" energy and indis "*ιι*" exergy. Besides indis "*dest*" is exergy destruction. Irreversibility in all thermal processes causes significant losses. In this respect, a general reference approach has been developed for design or system improvements. The potential for improvement in a system, especially with exergy analyses, is considered a reference for reducing entropy production in the system (Van Gool, 1997). Improvement Potential (*IP*) can be expressed as;

$$\dot{IP} = (1 - \eta_{Ex})\left(\sum \dot{E}x_{in} - \sum \dot{E}x_{out}\right) \tag{12}$$

Where η_{Ex} is exergy efficiency of the system and *Ex* is the total exergy for input and output of the system. The gain of losses due to irreversibility in systems is defined by *IP* and this is the reference potential in these design or improvement processes.

5. Sustainable environmental and economic criteria

Sustainable energy management in shipping companies will reduce fuel costs as well as operating costs. In this way, the economic evaluation criteria which can be applied for each ship can be developed by (individual) companies. Economic evaluation criteria have been developed along with the navigational planning of the ship, supported by power consumption and management, thermodynamics and life cycle analyzes. In this study, the "Energy Efficiency Index (EEI)" and the "Environmental Cost Index (ECI)" are developed based on the thermodynamic analyzes. The flow diagram of this process is given in Fig. 3.

As seen on the figure, shortly, economic evaluation criteria are developed based on the thermo-economic process and life cycle cost analysis. In this context, evaluations of ship operation are defined by four steps. After from the thermo-economics and life cycle analysis, economic performance criteria **ECI** and **EEI** are developed depending on these steps. The *ECI* should be seen as an impact of the direct loss fuel cost. Accordingly, the *ECI* is calculated as;

$$ECI = \frac{\sum \frac{I}{LHW} C_{fuel}}{\sum C_{fuel}} \tag{13}$$

Where "*I*" is exergy destruction, "*LHW*" is defined as low heat value of fuel, "*C*" is the cost of fuel. *ECI* is a loss cost effect in terms of direct loss analysis. This value can be seen as an activity criterion based directly on the operating parameters. Another economic performance criterion, *EEI*, is the criterion in which we define the relationship between exergy efficiency and Energy Efficiency Operational Index (*EEOI*).

$$EEI = \frac{\sum EEOI}{\eta_{II}} \tag{14}$$

Where "*ΔEEOI*" is change rate between EEOI and average EEOI and "η_{II}" is the average exergy efficiency of the voyage. The EEI should be seen as a benchmark criterion. It is a proportional comparison of ship's exergy on fuel with EEOI change. In these analyzes, the expectation is that the rate of change in the exchange rate is close to zero.

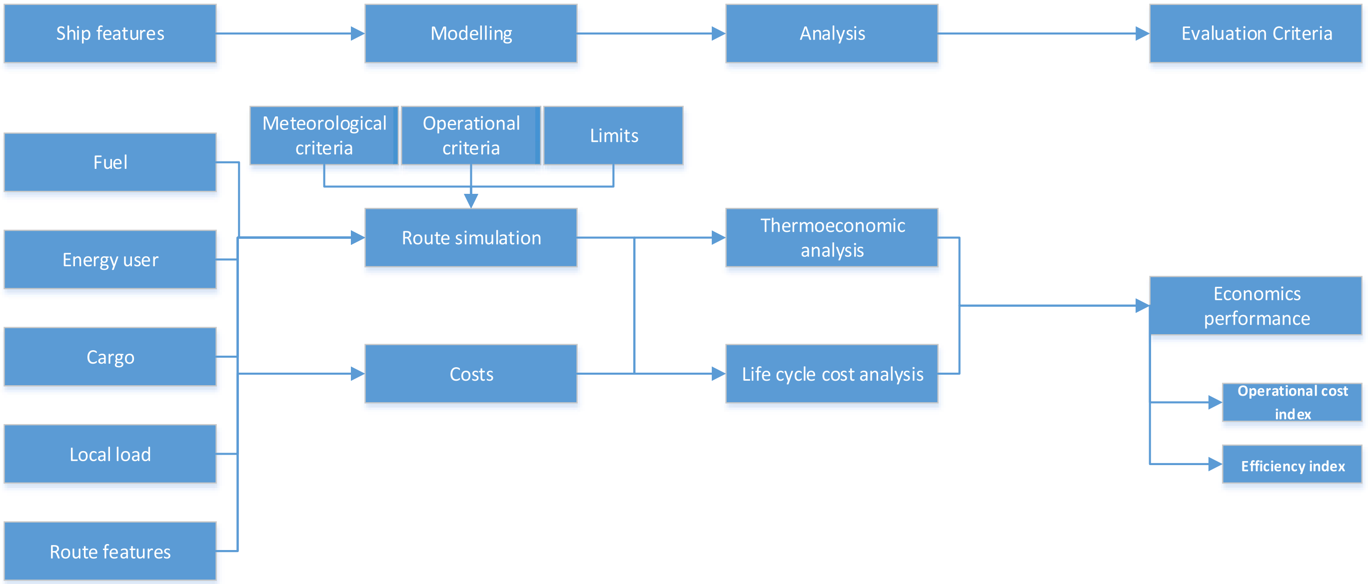


Fig. 3. Flow diagram of thermo-economic process.

6. Results and discussions

This study is primarily based on the energy efficiency strategy based on the holistic evaluation process of the ship. In this context, considering the number of voyages of the ship, all the elements based on efficiency were examined. In fact, in order to implement this strategy on ships, process related energy studies should be developed. This is the first step to define the efficiency potential. Then the process efficiency should be examined by energy and exergy analyzes. However, general performance evaluation can be carried out for decision-making processes on such ships without going through process analyses. With the statistical thermodynamic approach, the performance of the vessel can be calculated depending on the fuel consumption and power relationship. In this analysing process, it was considered firstly the performance evaluation of the energy efficiency strategy with reference to the voyage conditions of a cargo ship depending on available data. Later, the environmental and economic criteria, developed due to the performance of the ship, were examined. Together with the energy efficiency strategy, the information about ship's regular voyages was collected and data processed. The examined cargo ship had a capacity of 8100 kW diesel power. The ship proceeding, with an average occupancy rate of 83.17% and the total average of 17.651 tonnes, was consuming an average of 305 tons of fuel oil and diesel oil, including harbour period. In this study, depending on the strategy developed, the cruise parameters of the ship were taken into account 20 of the total 221 journeys are given as an example in Table 2.

For each time, during the voyage period between one port to the other and vice versa, it was examined the distribution of fuel consumption change by an average for 221 voyages and distributions is given in Fig. 4.

Significant changes were observed for the two criteria that were referenced in the fuel consumption of the ship. While a change rate of 40% was observed in time dependent consumption, a difference of 29.55% was found in the changes due to travel distance. However, when

Table 2
Some voyage parameters of the ship.

Voyage	Tonnage	Occupation Rate	Fuel Consumption		Consumption Rate at Sea		Total Voyage	
			Fuel-oil	Diesel	Fuel-oil	Diesel	Time	Distance
	Ton	%	Ton	Ton	%	%	Hours	Miles
1	8453.8	70.15	310.6	19.2	97.7	5.2	122.3	2372
2	8337	70.9	309.4	3	98.3	33.3	125	2372
3	7573.5	62	301.4	6.3	98.4	0	121.08	2372
4	9236.1	82.4	315.5	6	98.5	50	122.1	2372
5	7764.1	64	306.4	7.2	98.5	5.6	123.6	2372
6	8613.4	75.67	311.8	6.6	98.6	0	123.2	2372
7	10697.7	92.23	311.8	13.4	100	37.3	123.55	2372
8	9026.9	78.5	317.4	36	97.9	0	122.92	2372
9	8465.7	72.7	331.3	6	100	33.3	140.82	2686
10	9727.2	83.39	343.8	6.7	98.5	22.4	147.5	2732
11	5669.1	62.59	295.5	8.8	100	0	119	2372
12	9190	82.16	304.5	8	100	6.3	122.32	2372
13	9372.1	76.83	310.6	8.8	95.5	5.7	120.1	2372
14	9854	85.07	306.5	7.6	95.9	5.3	117.6	2301.5
15	9215.9	79.07	279.4	4.8	99.2	16.7	119.1	2301.5
16	9251.8	50.27	279	10.6	99.1	11.3	143.5	2372
17	10395.4	88.74	293	7.2	99.3	2.8	122.4	2372
18	8000.3	70.1	297.7	5.9	95.3	13.6	120.9	2372
19	11079.6	95.6	301	7.5	95.4	8	120.8	2301.5
20	9771.4	86.43	290.8	7.1	95.2	8.5	120.6	2372

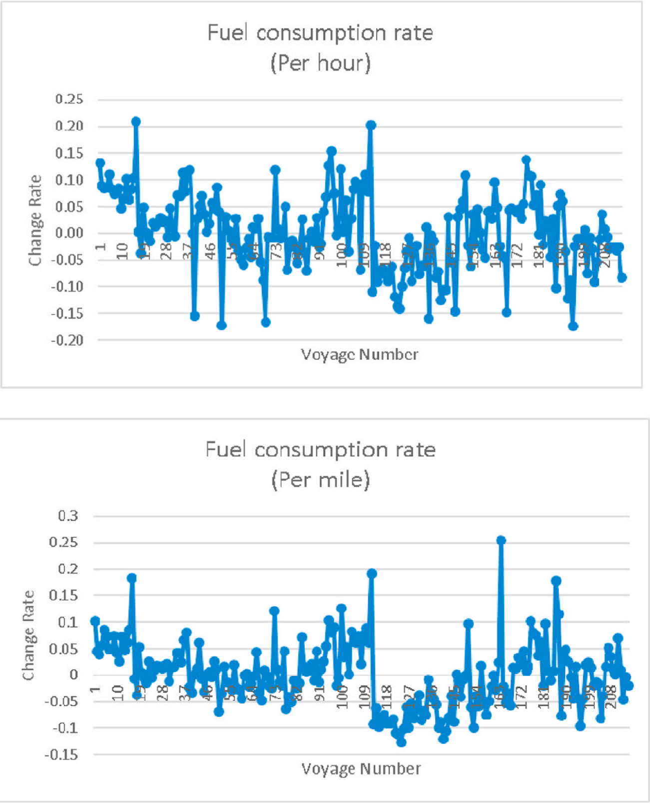


Fig. 4. The distribution of fuel consumption changes.

the commodity distributions (half load or full load) were evaluated, it was found that this change has a value of 103.58% per unit ton. In these fluctuations, it can be said that the performances also changed. In this respect, the engine load performances of the ship were evaluated for a full load. The performance analyzes were examined with energy and exergy analyzes based on thermodynamic laws. In this context, energy efficiency analyzes were performed using equations (1)–(4) and (10), as well as energy efficiency distributions for 100% power generation of the ship are given in Fig. 5.

Considering the consumption distributions, the average energy efficiency of the ship was found to be 38.33%. Considering that the ship has a total of 221 voyages, a distribution difference of approximately 47.84% is observed in efficiency performance. This ratio is quite remarkable considering the unit load effect. Also, considering the fact that the vessel does not operate continuously with a full load, the loss rate is an important potential. But the results can be obtained for each voyage. The analyzes were based on the thermal efficiency depending on the reference temperature. The energy efficiency strategy developed will yield the main outcome parameters for continuous improvement. This provides us with the opportunity to compare and evaluate for each voyage of the ship.

The voyage parameters of the ship were also examined in terms of exergy performance by taking into account the “dead state conditions”. In this framework, the exergy efficiencies of the ship voyages were calculated based on equation (11) and the results distribution is given in Fig. 6.

The average exergy yield for the entire process was found to be 35.82%. In this context, while the upper limit conditions in exergy efficiency were 45.70%, the change in performance was found to be 14.79%. All of these values were evaluated for the voyage parameters depending on the fuel consumption. The Sankey Diagram for energy performance of the process and the Grassmann Diagram for exergy performance are given below.

There are two types of efficiency ratios defined in the ship engine, namely the Sankey and Grassmann diagrams given in Fig. 7. The first is the efficiency obtained by power analysis and is expressed by an efficiency rate of 90%. The second is the efficiency analysis based on the thermal performance expressed as the ratio of the power obtained to the heat energy of the fuel burned. This is unfortunately not high (In the manual of the MAN engine the thermal theoretical efficiency is expressed as 50%). In this case study, irreversibility was evaluated according to statistical thermodynamic analyzes results considering exergy consept. The potential for loss, which is due to the irreversibility of the ship due to the energy management strategy, was evaluated in the improvement potential. Improvement potential is a measure of the ship’s exergy efficiency. In this context, this evaluation was made for each condition and exergy efficiency and related improvement potential distributions are given in Fig. 8.

Considering the exergy efficiency, the improvement potential of the ship in relation to the whole process was found to be 38.5% in fuel-based consumption only. This ratio refers to an important rate considered the emission and cost savings of the ship in terms of fossil fuel consumption. This potential shows that important actions on the ship operations must be applied with the energy efficiency strategic model developed especially for the operational indicators.

Evaluation criteria for energy efficiency in ships have sectoral criteria in terms of standards. The two main criteria, EEDI and EEOI, are the most common parameters adopted in the sector. Although EEDI is considered to be the design criterion of ships, the EEOI can be seen as a performance criterion based on direct voyage conditions. The mean EEOI-related changes of the ship were investigated for the referral process of voyages. The distributions are calculated in Fig. 9.

The mean EEOI value of the ship was found to be 39.19 g/t mile. According to this value, when the peak changes were taken as a reference, a cumulative total of over 80% was observed. In this context, the

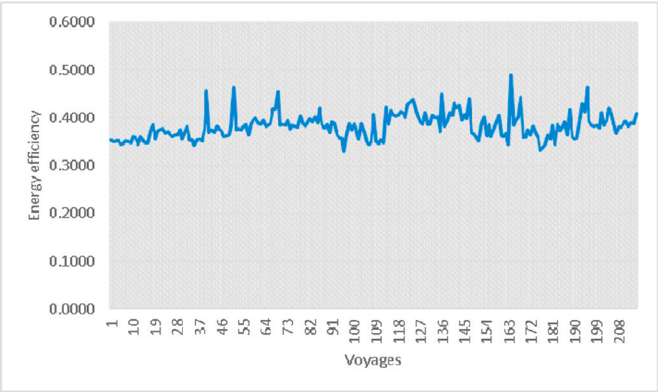


Fig. 5. The distribution of energy efficiency.

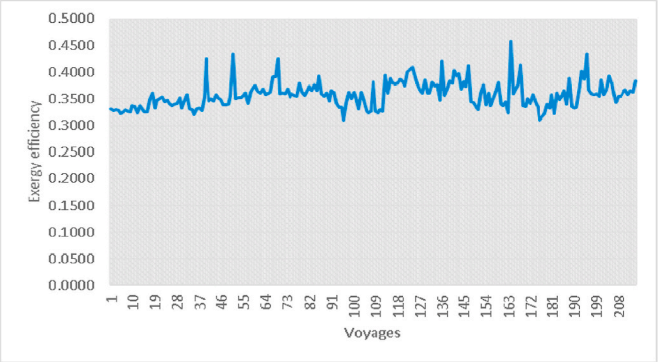
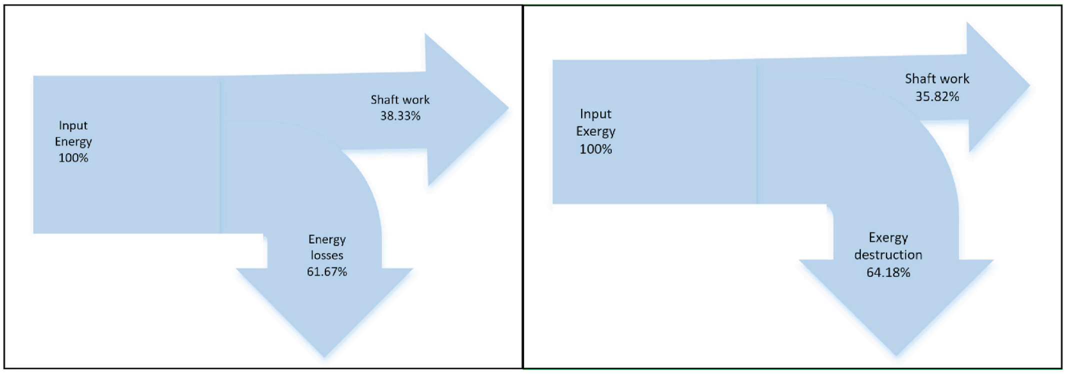


Fig. 6. The distribution of exergy efficiency.



a. Sankey diagram of voyage

b. Grassmann diagram of voyage

Fig. 7. Energy and exergy performance of the voyage.

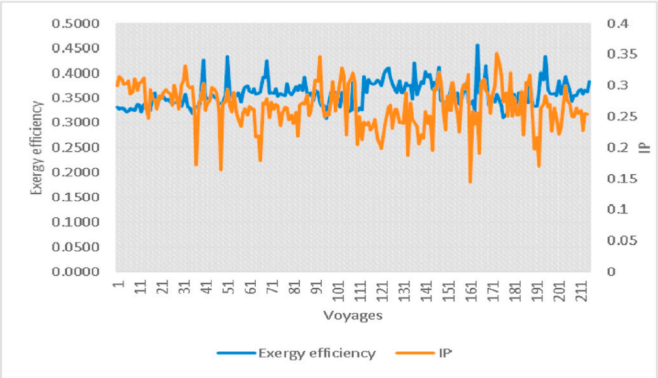


Fig. 8. The distribution of improvement potential considering exergy efficiency.

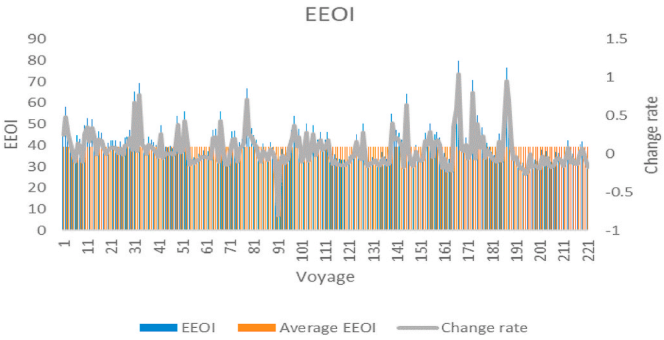


Fig. 9. EEOI for ship performance.

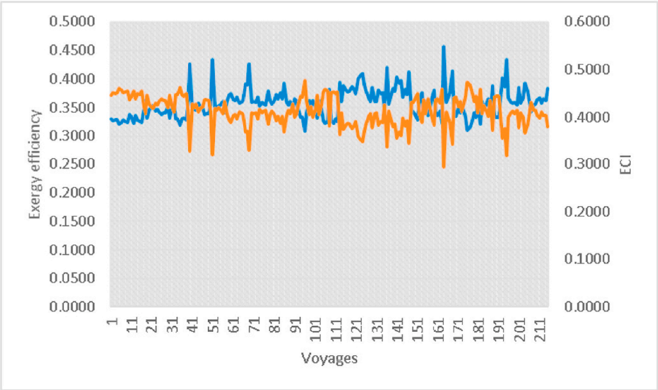


Fig. 10. Exergy efficiency and comparative analysis of ECI

ship's performance curve shows a very widespread distribution. This distribution has been evaluated as an important criterion for operational optimization in transportation conditions with multidimensional criteria in terms of international maritime enterprises. However, it is important to evaluate this in terms of economic performance criteria. Even though the fuel is followed by direct economic input by maritime companies, consideration of the issue in terms of the above performances is seen as a manageable measure in terms of energy efficiency. In this study, the ECI and EEI, defined as the economic criteria of the enterprise, are presented as important players of the developed strategy. When the system is considered for reversibility potential, the ECI distribution of the ship is given in Fig. 10.

The analysis shows the compatibility between ECI and exergy efficiency. It is seen that the environmental cost is increased in low efficiency and this effect decreases in high efficiency.

When analyzed the voyages of the ship, it was seen that the average ECI distribution was 0.41. However, when reversibility was taken into consideration, it was expected that this value, depends on the consumption in the navigational process, was average of 0.23. When looking at the system's loss potential, the average cost-loss associated with emissions was found to be 19.05%. In this context, ECI is a parameter to be taken into consideration directly in the evaluation of the ship's efficiency. The second criterion, EEI, refers to the relationship between EEOI and direct fuel consumption. In this context, comparative analyzes of the ship for the 221 voyages were discussed and the distributions are given in Fig. 11.

In the analysis, it was observed that the values were quite compatible due to exergy efficiency except for peak values. Specifically, the zero line can be taken as a reference value. In both directions, changes should be seen as a deviation from performance in fuel consumption and operating costs. Based on all these analyzes, the performance criteria of the ship were collected together and the evaluation criteria for the parameters are given in Table 3.

7. Conclusions

In this study, the performance analyzes and environmental impact analyzes were developed through economic criteria, with reference to the navigation process of the cargo ship. In this context, firstly, an efficiency strategy which is to be referenced onboard the ships is presented. Thermodynamic and the economic criteria have been established for sustainability criteria based on this approach. At the

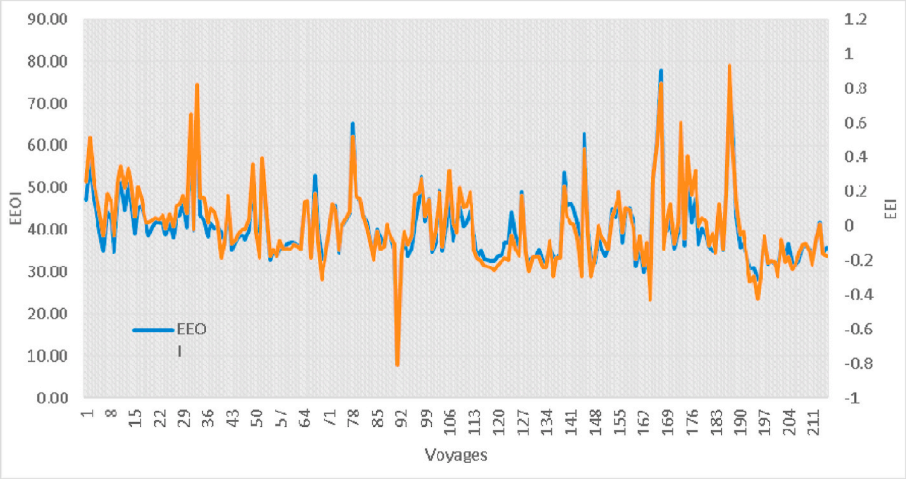


Fig. 11. Comparative analysis for EEI and EEOI.

Table 3
The performance summary of the ship voyages.

Ship parameters		Performance		Criteria	
Total Voyage	221	Energy efficiency (%)	38.25	ECI Standart	0.2252
Total miles	5,394,100	Exergy efficiency (%)	35.25	ECI Current	0.4126
Total load (tonnes)	2,126,673	Improvement rate (%)	38.5	EEI Current	1.18
Total time (hours)	28,550.93	EEOI	40.28	EEI Standart	1

same time, the criteria for strategic evaluation processes have been determined. In addition to the thermodynamic criteria, two new criteria have been defined in order to evaluate the economic effects of energy performance such as ECI and EEI. The following results were obtained from this study:

a. The thermodynamic analysis of the ship was done firstly and energy and exergy productivity were found to be 38.33% and 35.82% respectively.
b. The improvement potential for this ship was calculated to be 41.46%. In the study, ECI should be seen as the environmental impact of direct losses. In this context, when the average of the 221 voyages of this ship was taken into account, the ECI was 41.19%. According to the ideal efficiency conditions of this ship, the average loss rate in ECI was 19.05%, which means that there was considerable fuel loss.
c. EEOI is a criterion that is taken into account in marine enterprises. In this respect, considering the average EEOI, ship consumption had a change range of 80%. In this context, the operational losses were significant.
d. EEI directly demonstrates the impact of losses defined by EEOI. In this respect, it has been observed that it has a linear effect as regards the exergy efficiency.

It can be clearly seen from the above analyzes that fuel consumption can be reduced significantly by making performance improvements over the energy efficiency strategy for the shipping company. It has been assessed that the economic criteria defined in this study will supply important parameters for the decision-making processes based on energy management for vessels and therefore this, in turn, will provide a significant reduction in costs for maritime companies.

CRediT authorship contribution statement

Oktay Çetin: Data curation, Conceptualization, Writing - review & editing, Writing - original draft. **M. Ziya Sogut:** Conceptualization, Formal analysis, Writing - original draft, preparation, Methodology, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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