Journal of Marine Science and Application (2019) 18:185–194
https://doi.org/10.1007/s11804-019-00090-w

RESEARCH ARTICLE

Developing and Applying a Ship Operation Energy Efficiency Evaluation Index Using SEEMP: a Case Study of South Korea

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Received: 15 September 2017 / Accepted: 23 October 2018 / Published online: 10 April 2019

Abstract
The CO_2 emission reduction policy of the International Maritime Organization (IMO) recommends that the operation of ships, managed by maritime transport companies, should be energy-efficient. An evaluation method that can determine how successfully a ship implements the energy efficiency plan is proposed in this study. To develop this method, the measures required for energy-efficient ship operations according to the Ship Energy Efficiency Management Plan (SEEMP) operational guidelines were selected. The weights of the selected measures, which indicate how they contribute to the energy-efficient operation of a ship, were derived using a survey based on the analytic hierarchy process (AHP) method. Consequently, using these measures and their weights, a new evaluation method was proposed. This evaluation method was applied to shipping companies in South Korea, and their ship operation energy efficiency indices were derived and compared. This evaluation method will be useful to the government and shipping companies in assessing the energy efficiency of ship operations.

Keywords Ship · Greenhouse gas · Ship Energy Efficiency Management Plan · Energy Efficiency Operational Indicator · Energy Efficiency Design Index

1 Introduction

Due to the advancement of industries, the use of fossil fuel has increased and has exacerbated global warming. Global warming is responsible for serious environmental issues, such as climate change, rising sea levels, and destruction of ecosystems. Accordingly, efforts are being made at an international level to protect the environment by implementing measures to regulate global greenhouse gas (GHG) emissions. Since the UN Framework Convention on Climate Change (UNFCCC) in 1992, the international community has set targets to reduce GHG emissions for all the participating nations through the Kyoto Protocol of 1997. The regulation of GHG emissions from the marine transport industry has been delegated to the International Maritime Organization (IMO). The IMO has formed the GHG study group to facilitate GHG emission reduction focused on the Marine Environment Protection Committee's (MEPC) directive to reduce the current GHG emissions by 25%–75% using currently available technology and operation methods (Buhaug et al. 2009).

To reduce the typical GHG discharged from ships, the IMO created and circulated guidelines for the Energy Efficiency Design Index (EEDI) for newly built ships, the Energy Efficiency Operational Indicator (EEOI) for ships in operation, and the Ship Energy Efficiency Management Plan (SEEMP) at the 59th MEPC meeting. In 2011, at the 62nd MEPC meeting, a stipulation of SEEMP, which required all ships over 400 t undertaking international voyages to implement the SEEMP onboard from January 2013, was made

Article Highlights
• To reduce CO_2 emitted from existing ships, a method for evaluating energy-efficient operation was developed using the Ship Energy Efficiency Management Plan (SEEMP) as well as Energy Efficiency Operational Indicator (EEOI) regulations.
• A survey based on the AHP method was conducted to develop an energy evaluation index.
• By comparing the energy efficiency index scores assigned to marine transport companies, operational corrective measures to decrease CO_2 emissions could be determined.

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mandatory (Resolution MEPC.203(62)). Later, the IMO released a new standard guideline for SEEMP (IMO MEPC. 282(70), 2016) and amendments to MARPOL Annex VI related to the data collection system, which came into force on March 1, 2018.

Moreover, as the Kyoto Protocol will expire in 2020 (CMP8), the new climate system (Post-2020) has started to receive attention. Post-2020 was established in Durban, South Africa, in 2011, and is a protocol for all the developed and developing countries to bear the obligation of GHG reduction after 2020. The United Nations Climate Change Conference (COP20) held on December 2014 proposed the Intended Nationally Determined Contributions (INDC) plan (Decision 1/CP.20). Accordingly, INDC has been submitted, first by Switzerland. As for the goals of the major countries, Switzerland, a developed country, plans to reduce GHG emissions by 50% of the 1990 levels by 2030 (Switzerland's INDC). The USA has submitted a reduction goal of 26%–28% of the 2005 levels by 2025 (US INDC). Korea, categorized as a developing country, aims at 37% reduction by 2030 (Republic of Korea INDC 2014). To achieve such goals, regulations to reduce CO_2 are required for all industries. Therefore, a tool to evaluate and inspect the CO_2 reduction activity of each industry is necessary. As a result, there have been continued relevant studies in line with this international trend. The studies in the marine transport field include those on the trends of regulations on CO_2 discharged from IMO ships, energy efficiency indices (EEDI, EEOI), and the SEEMP.

First, several studies have been conducted on the trends of IMO CO_2 regulations. They mainly discuss IMO CO_2 regulations, technological measures of EEDI, operational measures of EEOI and SEEMP, and market-based measures (MBMs). Kim (2010) and Harilaos (2012), in their studies, described energy efficiency indices of EEDI and EEOI, especially regarding MBM. A study by Jung (2011) was based on the approximate details of EEDI, EEOI, and SEEMP. Moreover, the CO_2 emission regulations that may take effect in the future have been investigated and analyzed. Lee et al. (2011) studied the development process of climate protocols and IMO's GHG emission regulation trends. Through the above studies, it has been pointed out that IMO's GHG emission regulations have limitations and shortcomings. Such studies have mainly focused on suggesting directions based on the corresponding trends. However, they do not engage in investigating the practical application of methods or performance evaluation for the marine transport companies and the governments that implement the related stipulations.

Second, several studies have proposed and determined energy efficiency indices (EEDI, EEOI). Devanney (2010) proposed a method through which a very large crude carrier (VLCC) designer can achieve the EEDI standards and investigated the influence of EEDI on VLCCs. Choi et al. (2015) proposed a new EEOI formula, which calculates fuel consumption per kW as an alternative to the calculation of CO_2 emission according to freight transport, as proposed by IMO. Moreover, Lee (2014) noted that the current IMO EEOI considers that an empty ship with no freight does not emit CO_2, which leads to error; as a result, the EEOI formula was modified such that the ballast amount in the empty ship would be treated as the freight amount. Barro et al. (2011) developed a software that can monitor EEDI and EEOI. The above studies focus on improving the formula for energy efficiency indices; however, they are focused only on developing the energy efficiency indices and are thus inadequate in terms of applying and reflecting the results of these indices on ship operation.

Third, there have been studies on methods for SEEMP education and operation. Baldauf et al. (2013) proposed an education system for energy-efficient operation, namely Model Route, which is based on the guidelines for energy-efficient operation proposed by SEEMP. Yoo et al. (2015) and Lokukaluge et al. (2017) proposed methods of the optimal route selection, through simulation by applying climate and marine data. The IMO also developed a model course on SEEMP, promoting the energy-efficient operation of ships to assist trainers (IMO 2014). Lee (2014) and Lokukaluge et al. (2015) conducted investigations to determine the optimal trim of ships. These studies compared the amount of fuel conserved based on the fuel-saving antifouling paint and trim changes. Armstrong and Banks (2015) and Tran (2017) conducted case studies on energy efficiency operation and EEOI calculation, respectively. Adland et al. (2018) showed the effectiveness of periodic ship hull cleaning on energy conservation.

Finally, Choi et al. (2015) examined the current application status in the marine transport companies implementing SEEMP. Various issues were found in the implementation of SEEMP by marine transport companies, leading to a proposal of corresponding enhancement plans. Such studies focus on revealing the relationship between the details of energy-efficient operation guidelines and the ship's energy-efficient operation. However, studies on the techniques for the utilization and evaluation of ship operation energy efficiency guidelines are rare.

To summarize the studies conducted so far, the overall contents of the IMO CO_2 emission regulations have been studied and issues with the enforcement of EEDI and SEEMP have been discussed. Studies have also been conducted on EEDI and EEOI and on improving the EEOI formula. Regarding SEEMP, studies are being conducted on the fuel conservation effect of each item of the SEEMP energy-efficient operation guidelines. Moreover, it has been verified that marine transport companies face various issues in the implementation of the early-stage SEEMP. This trend of related studies shows that the interest of marine transport companies in energy-efficient ship operation is increasing, and a study on the evaluation and management of energy-efficient ship operation by the marine transport industry is urgently required.

Accordingly, a method to evaluate energy-efficient ship operation was developed in this study. This method can evaluate whether a marine transport company is executing SEEMP appropriately and efficiently. With the help of this method, the government or related organizations can evaluate whether the operation of ships by marine transport is energy-efficient. To develop this evaluation method, we selected the essential operational measures that contribute significantly to an energy-efficient ship operation based on the operational guidelines of SEEMP. To calculate the weighting, which indicates the contribution of the selected measures to an energy-efficient ship operation, a survey based on the analytic hierarchy process (AHP) method was conducted among the marine transport companies and ship operations experts. With the help of the selected energy-efficient ship operation items and the weighted value of each item, the evaluation method can determine the level of energy efficiency of a ship operated by a marine transport company. Finally, the developed ship operation energy efficiency evaluation method was utilized to calculate the energy-efficient operation indices of marine transport ships and the results were compared. As a result, the level of energy-efficient ship operation for each marine transport company could be determined quantitatively. The evaluation method proposed in this study can be useful in the evaluation and management of energy-efficient ship operations by the government or marine transport companies. Additionally, it can also be utilized in international GHG reduction policies.

2 Ship Energy Efficiency Management Plan

2.1 Concept of SEEMP

The SEEMP intends to reduce the CO_2 emissions from ships. Since January 1, 2013, all ships over 400 t have been expected to implement the SEEMP onboard (Resolution MEPC.203(62)). This guideline was later updated to reflect the new guidelines suggested by IMO (IMO Resolution MEPC. 282(70), 2016).

According to the new guideline, SEEMP consists of four stages, planning, implementation, monitoring, and self-evaluation/improvement as shown in Fig. 1. The gradual improvement of energy-efficient operation should be achieved through the continued repetition of these four stages. Moreover, IMO recommends the use of EEOI at the monitoring stage to monitor the energy efficiency of the ships.

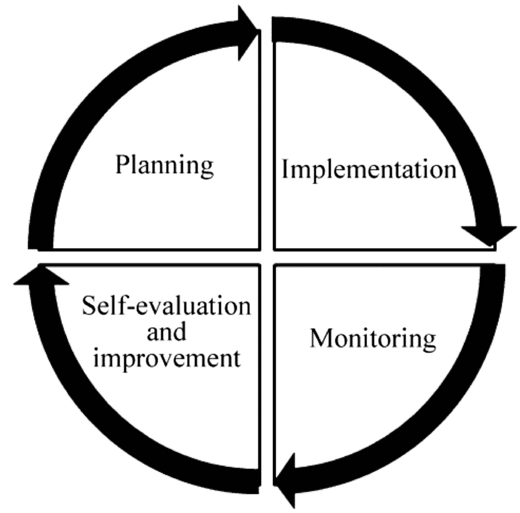

Fig. 1 Process of SEEMP

2.2 Energy Efficiency Operational Indicator

The EEOI suggests the amount of CO_2 emitted from a ship when transporting 1 t of freight by 1 nautical mile. In other words, this indicator evaluates the efficiency of transportation by calculating the amount of CO_2 emitted per actual transported ton. It is expressed as shown in Eq. (1) (IMO 2009b), where FC_j is the mass of consumed fuel at voyage (j indicates the fuel type); C_{Fj} represents CO_2 conversion factor; m_{cargo} denotes cargo carried (tons) or work carried out (number of TEU or passengers) or gross tons for passenger ship; and D is the distance in nautical miles corresponding to the cargo carried or work carried out.

$$\text{EEOI} = \frac{\sum_j \text{FC}_j \times C_{Fj}}{m_{\text{cargo}} \times D} \tag{1}$$

The EEOI of each voyage varies significantly and depends on the voyage characteristics (climate, route, device performance), making long-term analysis of a ship's energy efficiency difficult. Therefore, IMO recommends the use of rolling average EEOI, which is the average value of EEOI over a certain period (10 voyages), as shown in Eq. (2). Thus, EEOI is used as a tool to verify a ship's energy efficiency by calculating the CO_2 emission incurred by fuel consumption in a ship.

$$\text{Rolling average EEOI} = \frac{\sum_i \sum_j \left(\text{FC}_{ij} \times C_{Fj}\right)}{\sum_i \left(m_{\text{cargo},i} \times D_i\right)} \tag{2}$$

where i is the voyage number.

2.3 Guideline for Energy-Efficient Ship Operation

The SEEMP guideline (IMO MEPC.282 (70), 2016) has 13 categories of measures for the improvement of a ship's energy efficiency, as shown in Table 1, with 20 detailed measures. The IMO recommends that marine transport companies implement the proposed measures (Table 1), with the aim of achieving goals such as fuel conservation and environmental protection.

3 Ship Operation Energy Efficiency Evaluation Method

The IMO promotes environment protection by setting global GHG reduction targets and enforcing the SEEMP. The SEEMP implementation by marine transport companies is expected to enable ship CO_2 emission reduction and energy-efficient ship operation. However, according to the existing studies (Choi et al. 2015), the research on SEEMP, as well as its implementation, is still in the elementary stages. This explains the various issues found in the SEEMP implementation by marine transport companies. Moreover, at present, there is no method to evaluate and analyze the energy efficiency of a ship operation. In this study, such method is proposed.

Table 1 Guidance on best practices for fuel-efficient operation of ships

1. Fuel efficient operations
1.1 Improved voyage planning
1.2 Weather routing
1.3 Just in time
1.4 Speed optimization
1.5 Optimized shaft power
2. Optimized ship handling
2.1 Optimum trim
2.2 Optimum ballast
2.3 Optimum propeller and propeller inflow consideration
2.4 Optimum use of rudder and heading control system (autopilots)
3. Hull maintenance
4. Propulsion system
4.1Propulsion system maintenance
5. Waste heat recovery
6. Improved fleet management
7. Improved cargo handling
8. Energy management
9. Fuel type
10. Other measures
11. Compatibility of measures
12. Age and operational service life of a ship
13. Trade and sailing area

3.1 Evaluation Index Development Process

The development process of the ship operation energy efficiency evaluation method is as shown in Fig. 2. First, through brainstorming, the essential operational measures that were considered to contribute significantly to the energy-efficient operation of ships according to the SEEMP guidelines (IMO MEPC.282(70), 2016) were selected and hierarchized. Subsequently, through a survey using the AHP method, the importance of essential operational measures was calculated. Then, we developed an evaluation method for the energy-efficient ship operation using the calculated importance levels.

The AHP method used for the survey was devised by Saaty in the 1970s. It is a multi-criteria decision-making method in which multiple evaluation criteria are hierarchized, and their importance is consequently determined based on the hierarchy (Saaty, Saaty and Wind 1980). Through empirical analysis and a precise mathematical verification process, this method is utilized in various techniques used in criterion selection, weighting calculation results, and sensitivity analysis; it is theoretically the most highly evaluated among the existing decision-making methods. The AHP method comprises the following four steps (Bhushan and Rai 2004):

1) *Hierarchization*: The issue to be analyzed is structured as goal, criteria, sub-criteria, and alternative. The top hierarchy is goal; the middle is criteria, which influences the decision-making; and the bottom is the alternative to the decision-making.
2) *Paired comparison*: Data collection is achieved through the paired comparison method. This method mutually compares two evaluation items, while the evaluator compares the importance of each item on a nine-point scale, as shown in Table 2.
3) *Determination of weighted value and priority*: Through paired comparison, subjective judgments are converted to

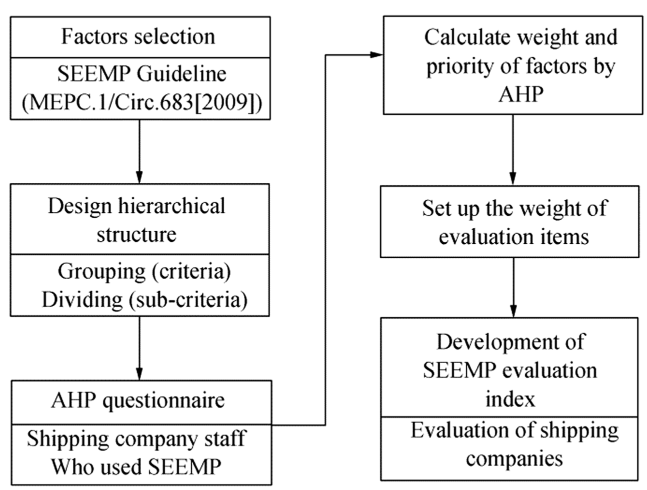

Fig. 2 Process for the development of evaluation index

numerical values according to the scale, using matrix eigenvector method. The weighted value refers to the priority vector. It is interpreted as the relative importance of or preference for each item.

4) *Consistency check*: The reliability of the paired comparison is determined by the consistency ratio (CR). For CR calculation, the consistency index (CI) of the $n \times n$ matrix must be first determined using Eq. (3). Here, λ_{max} denotes the maximum eigenvalue of the judgment matrix and n is matrix dimension. The CR is calculated as the ratio of random index (RI) to CI. The result is deemed reliable only if CR is less than or equal to 0.1 (Jovanović et al. 2015).

$$CI = \frac{\lambda_{max} - n}{n - 1}, CR = \frac{CI}{RI} \tag{3}$$

3.2 Selection of Evaluation Items

To execute hierarchization, which is the first step of the AHP method, the items related to the issue to be evaluated must be selected. For this, a brainstorming session was conducted. On the basis of the measures recommended for energy-efficient operation in the SEEMP guideline, as suggested in Table 1, the essential operational measures were determined. The final hierarchy of the evaluation items for energy-efficient ship operation is shown in Fig. 3.

As shown in Fig. 3, level 0 of the hierarchy—the final goal—is energy-efficient ship operation. Lower hierarchies comprise 5 criteria at level 1 and 15 sub-criteria at level 2. The sub-criteria were selected from items corresponding to the energy-efficient ship operation among the measures recommended in the SEEMP guideline. The 15 sub-criteria were grouped based on similar characteristics, such that they belonged to the corresponding criteria of the upper hierarchy.

The level 1 criteria consist of pre-sailing measures, measures during sailing, engineering, ship maintenance, and technology. These criteria are explained as follows.

The first criterion of level 1, pre-sailing measures, refers to measures that can be implemented before the ship sets sail. Pre-sailing measures include optimal route planning (design) and information exchange. Optimal route planning contributes to fuel conservation by utilizing climate information to select the shortest route. Information exchange refers to land-sea communication or communication among crewmen. For example, information regarding entry harbors can be shared to avoid unnecessary standby. Moreover, exchange of information such as climate/marine conditions among navigators and engineers can enable the implementation of appropriate measures on the ship, such as service speed or fuel supply plan.

Table 2 Gradation scale for the quantitative comparison of alternatives

Option	Numerical value/s
Equal	1
Marginally strong	3
Strong	5
Very strong	7
Extremely strong	9
Intermediate values	2, 4, 6, 8

The second criterion, measures during sailing are measures that can be implemented for fuel conservation during sailing. Mid-voyage measures include economical speed compliance, appropriate trim compliance, appropriate ballast compliance, and autopilot usage optimization. Fuel consumption is proportional to the cube of the ship speed. Therefore, economical speed compliance has a significant influence on the fuel consumption, making it the most efficient fuel reduction method. Trim affects the hull resistance. Ships must be efficiently operated using the appropriate trim. In addition, ballast determines displacement. Since displacement is proportional to 2/3 of the power of fuel consumption, it must be considered for fuel conservation. Moreover, the optimal use of autopilot can reduce unnecessary rudder use, allowing the efficient operation of rudder.

The third criterion, engineering, is the energy-efficient ship operation measure that includes optimal RPM maintenance, main engine optimization, and fuel additive usage. Maintaining a certain RPM helps to maintain a certain speed through engine output. Moreover, the fuel efficiency of the main engine is largely influenced by the conditions of the engine components. Therefore, the devices must be maintained in the optimal state. The use of fuel additives can effectively reduce sludge formation and enhance spray pattern, leading to fuel conservation.

The fourth criterion, ship maintenance, refers to aspects such as hull cleaning, propeller polishing, and fuel-saving paint. These contribute to reducing the ship's resistance. Hull cleaning is for evaluating the fouling state of the hull, while propeller polishing helps with improving the propulsion energy efficiency. These two tasks should be executed regularly through inspection. Fuel-saving paint forms a smooth surface on the exterior plating of the hull, resulting in fuel conservation.

The final criterion, technology, refers to the measure of the application of new technologies for the efficient operation of the ship during its construction or repair. This measure includes efficient propeller installation, application of a waste heat recovery system (WHRS), and use of alternative energy. The installation of an efficient propeller can reduce the turbulence of the propeller and improve the propulsion efficiency of the ship. Meanwhile, the use of a WHRS can increase energy efficiency by recycling the waste heat from the main engine to reduce the fuel consumption.

Therefore, the evaluation items proposed in Fig. 3 are measures that need to be executed for energy-efficient operation. A marine transport company can significantly contribute to

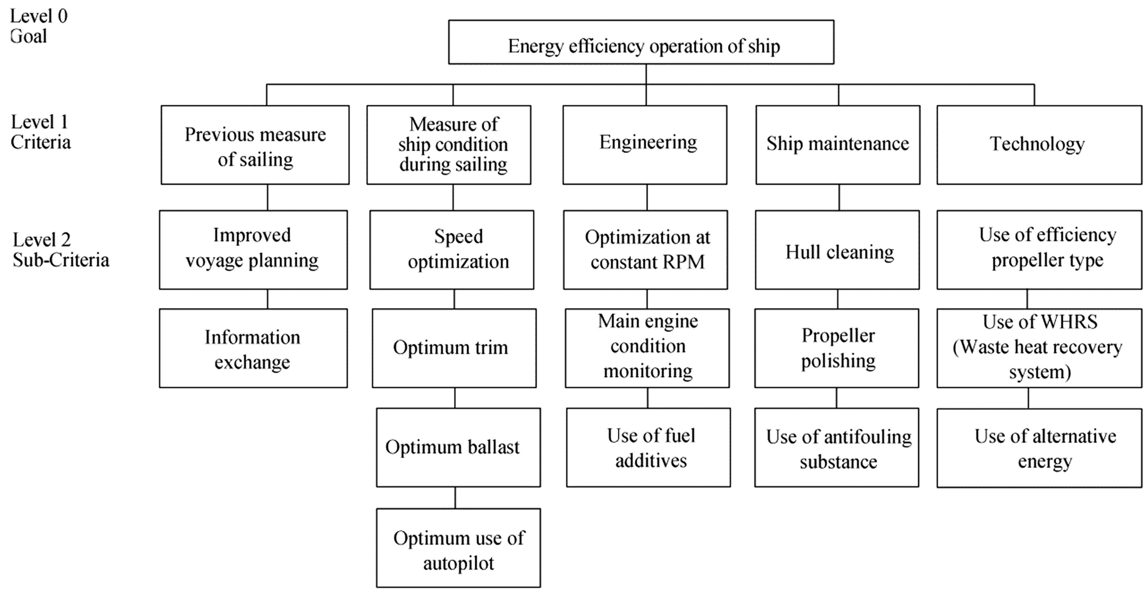

Fig. 3 Hierarchy for evaluation of a ship's energy efficiency

reducing a ship's CO_2 emissions by implementing all these evaluation items.

3.3 Survey

After the hierarchization of the evaluation items, each element should be relatively weighted. This step is achieved through a paired comparison of items at the same hierarchical level. Accordingly, in this study, a survey was conducted among ship operation experts and those working in marine transport companies that implement the SEEMP.

An AHP-based survey with nine-point scale was used for a paired comparison of each item. The survey was conducted for 3 weeks, from November 15, 2014, to December 5, 2014, through self-administration and survey e-mails. A total of 50 surveys were distributed, of which 42 were collected. Of these, 35 surveys, excluding 2 inadequate responses and 5 low-consistency responses, were used in the AHP analysis. Among the 35 surveys, the response rate per ship type is as shown in Fig. 4. Additionally, during the survey, the application status of the sub-criteria related to energy-efficient operation was investigated. The data thus collected were used to evaluate marine transport companies with the developed evaluation index.

3.4 Analysis Results and Evaluation Index Development

To calculate the weightings, the AHP software "MakeIt" was used. This software delivers consistency ratio (CR) as the output, with the input as the nine-point scale value of paired comparison. The data from the collected surveys were entered into the software. The surveys with a CR of 0.1 or above were sent for resurvey. However, these surveys were excluded from the AHP analysis, despite the resurvey request. Finally, 35 surveys that obtained a CR of 0.1 or below were used to determine the weightage of the evaluation items. The AHP analysis results are as shown in Table 3 and Fig. 5.

As shown in Table 3, the second among the five criteria at level 1, measures during sailing, was found to be the most important with a weighted value of 0.2602. Among its sub-criteria, economical speed compliance (0.1185) showed the highest weighted value. In contrast, the fifth criterion of level 1, technology, showed the lowest weighted value (0.1163). Among the 15 sub-criteria, optimal route planning (0.1329) was found to be the most essential operational measure. Figure 5 shows the weighted value of each essential

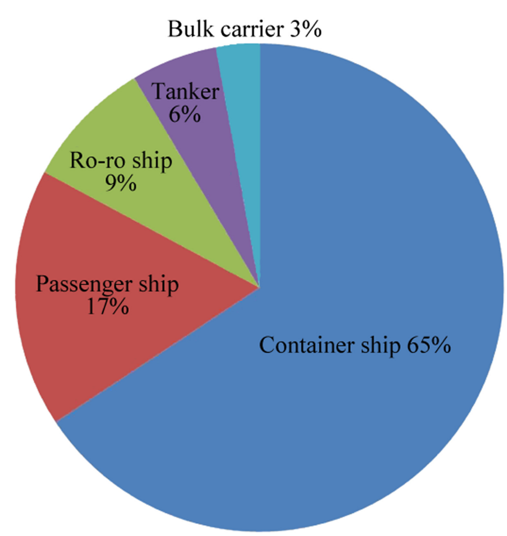

Fig. 4 Ratio of questionnaire according to ship type

Table 3 Weightage of the evaluation items

Criteria	Sub-criteria	Weight
Pre-sailing measures (0.2000)	Improved voyage planning	0.1329
	Information exchange	0.0671
Measures during sailing (0.2602)	Speed optimization	0.1185
	Optimum trim	0.0584
	Optimum ballast	0.0526
	Optimum use of autopilot	0.0307
Engineering (0.2545)	Optimization at constant RPM	0.1209
	Main engine condition monitoring	0.0974
	Use of fuel additives	0.0362
Ship maintenance (0.1690)	Hull cleaning	0.0715
	Propeller polishing	0.0476
	Use of antifouling substance	0.0500
Technology (0.1163)	Use of efficiency propeller type	0.0518
	Use of WHRS	0.0336
	Use of alternative energy	0.0309

operational measure, representing their respective importance, in order.

Using the weighted value of the items required for energy-efficient ship operation, a method for calculating the ship operation energy efficiency evaluation index was developed as shown in Eq. (4), where W_i is the weight of the application items.

$$\text{Evaluation score} = \sum W_i \tag{4}$$

The sum of the weighted values of the evaluation items at the same level in the AHP method is 1. Therefore, the maximum value of Eq. (4) is 1, which means that the implementation of all the sub-criteria during ship operation will be attributed the maximum value of 1.

This evaluation index can assign a numerical value to the level of energy-efficient operation of each ship. It is a tool that can directly indicate how many energy-efficient operation measures are being implemented. Using this index, a marine transport company can easily recognize the level of energy efficiency of each ship in operation. Moreover, the government or related organizations would be able to recognize the contribution of a marine transport company to CO_2 reduction through energy-efficient operation.

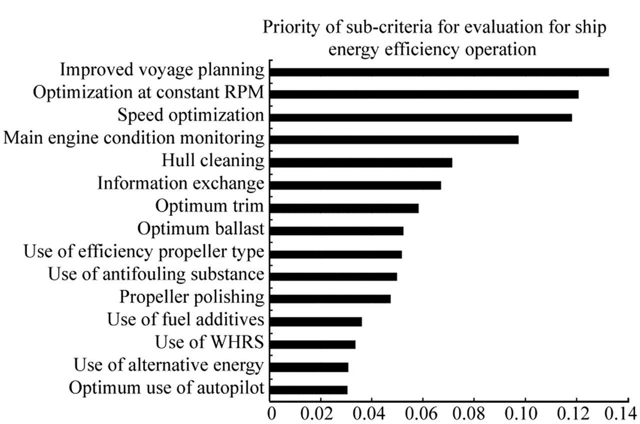

Fig. 5 Priority of evaluation items

4 Application of Ship Operation Energy Efficiency Evaluation

In this section, the ship operation energy efficiency evaluation index developed in the previous section was applied to evaluate energy-efficient ship operation by marine transport companies. Five companies were selected as the subjects. The main ships operated by each company are as shown in Table 4. Through the survey, we investigated whether the 15 detailed measures for energy efficiency evaluation were being implemented or not. Each company was interviewed, and they mentioned which of the ship operation energy efficiency measures they currently implemented.

Table 5 presents the details of the measures being implemented for an energy-efficient ship operation. According to this table, the number of implemented measures varies greatly among companies. Moreover, some measures were more implemented than others. With regard to each item, the level 1 criterion of pre-sailing measures was found to be implemented by almost all companies. However, the criterion of technology, which was only applicable to newly built ships, was not being implemented by all companies. Based on these investigation results, the energy-efficient operation index of each marine transport company was determined. The ship operation energy efficiency evaluation method proposed in Sect. 3 was used. The calculated energy-efficient operation indices of the companies are as shown in Fig. 6.

According to Fig. 6, company B, which operates a passenger liner, was found to be implementing energy-efficient ship operation measures most successfully, with an energy-efficient operation index of 0.8856. It was followed by companies D, C, A, and E.

Companies B and D, which were evaluated to be successfully carrying out energy-efficient operation, were found to be implementing almost all measures, such as pre-sailing measures, measures during sailing, and engineering, which

Table 4 Main vessels of marine transport companies evaluated using the evaluation index

Company	Main vessel
A	Passenger ship
B	Ro-ro ship
C	Container ship
D	Container ship
E	Tanker

Table 5 Implementation of energy-efficient ship operation measures

Criteria	Sub-criteria	A	B	C	D	E
Measures before sailing	Improved voyage planning	X	O	O	O	O
	Information exchange	X	O	O	O	O
Measures of ship condition during sailing	Speed optimization	O	O	O	O	O
	Optimum trim	O	O	O	O	X
	Optimum ballast	O	O	O	O	X
	Optimum use of autopilot	O	O	O	O	O
Engineering	Optimization at constant RPM	O	O	O	O	O
	Main engine condition monitoring	O	O	O	O	X
	Use of fuel additives	X	O	X	O	X
Ship maintenance	Hull cleaning	O	O	O	O	O
	Propeller polishing	O	O	O	O	X
	Use of antifouling substance	X	X	X	X	O
Technology	Use of efficiency propeller type	X	O	X	X	X
	Use of WHRS	X	X	X	O	X
	Use of alternative energy	X	X	X	X	X

significantly contribute to the energy-efficient operation among the level 1 criteria. Such aspects were determined to be the reason for their high score on the energy-efficient operation evaluation. Moreover, operating younger ships, to which technology for energy efficiency was applied, also resulted in high scores.

In contrast, the reasons for the relatively low scores of companies in the ship operation energy efficiency evaluation were as follows: company E, with the lowest score, operates an old ship, and as a result, the level 1 criterion of technology was not applied at all. The criteria of measures during sailing and engineering, which contribute significantly to an energy-efficient operation, were implemented relatively poorly compared to their implementation by other companies. For company E to achieve a high score in the energy-efficient operation evaluation in a short period of time, instead of adopting new technology, which requires high expenditure, it should implement items that can increase the ship's energy efficiency during operation, such as those related to the pre-sailing measures and measures during sailing.

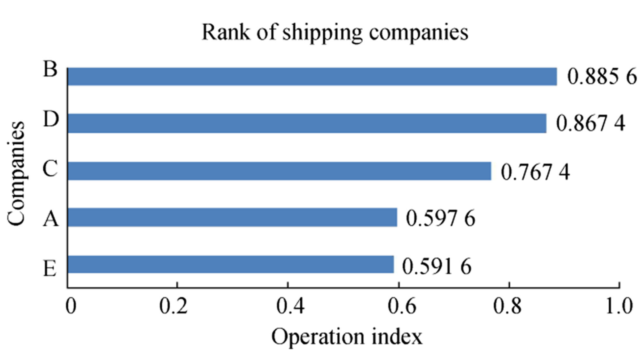

Fig. 6 Calculated energy-efficient operation index

Overall, for a marine transport company to achieve a high energy-efficient operation index, it must execute as many of the detailed energy-efficient ship operation measures found to contribute significantly to an energy-efficient operation as possible. Moreover, operating a younger ship can reduce the CO_2 emission of the ship due to the use of upgraded technology in their operation.

5 Conclusion

The IMO has enforced the SEEMP for GHG regulation in the marine transport sector. The SEEMP aims to reduce CO_2 through energy-efficient operation of marine vessels. However, marine transport companies face several hurdles in implementing the SEEMP. Therefore, this study evaluated energy-efficient ship operations on the basis of the SEEMP guidelines. The process and results are summarized as follows.

First, we developed a ship operation energy efficiency evaluation method that can determine the energy efficiency of ship operations managed by marine transport companies. We realized this via the following process:

1) Items contributing to energy-efficient ship operation according to the SEEMP guideline were determined. These were grouped and selected as the final energy-efficient ship operation items.
2) A survey based on the AHP method was conducted to assign a numerical value to the level of contribution of each energy-efficient ship operation item.

3) Using the weighted values of energy-efficient ship operation items, a ship operation energy efficiency evaluation index was developed.

Second, using the developed evaluation method, the operations of five marine transport companies were evaluated for energy efficiency. Through the evaluation, each company was assigned an energy-efficient ship operation index. Through a general analysis of the index score of each company, we could propose improvements required for higher scores, i.e., recommendations for further improving energy efficiency.

The proposed ship operation energy efficiency evaluation method allows marine transport companies to recognize the energy-efficiency level of their current ship operations. Moreover, the government and related organizations can utilize the method as a tool to evaluate and manage each marine transport company. Such evaluation can encourage energy-efficient ship operations among companies, and it can be utilized in CO_2 reduction policies and establishment of energy-efficiency systems.

In the future, through the utilization of a ship's EEOI value and the evaluation index developed in this study, additional studies on the correlation of EEOI with the index score are expected to further advance the CO_2 reduction policies and ship operation energy efficiency evaluation method.

Funding The authors would like to acknowledge the support from the project titled "Development of Ship-handling and Passenger Evacuation Support System" funded by the Ministry of Oceans and Fisheries (South Korea-MOF).

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