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ARTICLE

A multi-aspect framework to support the decision-making process of low carbon emission solutions

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Abstract
The aim of 2 °C global temperature gaining limitation had been included in the Copenhagen Accord emerging from the Conference of Parties (COP15) meeting. The Ship Energy Efficiency Management Plan (SEEMP) and Energy Efficiency Design Index (EEDI) became mandatory and served as a guide for companies in low-carbon operation and management. However, the actual active application of low-carbon shipping (LCS) measures by stakeholders still undeniably plays a decisive role. Unfortunately, the way from SEEMP and EEDI adoption to LCS measures implementation of industrial stakeholders remain knowledge gaps. One of them is a manner by which LCS measure decisions can be made properly by considering multiple criteria. This paper, by analyzing primary internal and external factors affecting LCS decisions, introduced a decision-making framework for shipping companies in choosing the most appropriate LCS measures for individual ships to implement in diversified conditions. The framework has a generic structure thus researchers and policymakers, as well as each company can apply it flexibly and diversely.

Keywords Ship energy efficiency management plan (SEEMP) · Decision-making framework · Low-carbon shipping (LCS) · Energy efficiency design index (EEDI)

1 Introduction

There are pieces of research indicated that maritime transport contributes a significant proportion of approximately 3% of global CO_2 emissions (Buhaug et al. 2009;

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Dalsøren et al. 2009; Endresen et al. 2008) and 7–9% of global diesel black carbon in 2000 (Azzara et al. 2015). In addition, the fact that bunker cost often represents around 60–70% of general vessels voyage costs can be observed from practice (Transparency Market Research 2014) and academic examples (Branch and Robarts 2014; Stopford 2009). Economic returns from better energy efficiency play an important role as a motivation for the trend of low-carbon shipping (LCS). The cost-effective method approach of Hoffmann et al. (2012) displayed an auspicious CO_2 curbing potential of 30% and 53% CO_2 decrease with measure-by-measure and set of measures application model respectively by the time of 2030. As the adoption of the SEEMP, its recommended key indicator, i.e., the Energy Efficiency Operational Indicator (EEOI) and the EEDI, shipping companies are having the greatest chance ever to approach and achieve the energy efficiency and environment-friendly shipping using LCS measures.

As the environmental awareness of the industry becomes higher, ship designers, builders, operators, and owners are now coping with progressively a newer and tougher environmental framework (Smith et al. 2014). At the moment, EEDI is considered as the most important technical instrument in an attempt to reduce the CO_2 emission from the world fleet by setting a baseline for energy efficiency of new ships. As long as the required level is attained, ship designers/builders are free to use the most cost-effective LCS measures to comply with regulations. On the other hand, the SEEMP established a mechanism to urge the ship owners and operators to consider new cost-effective technologies and practices in ship operations; it awakes and encourages ship owners and operators to observe the bright side of applying energy efficient measures to achieve both greener and more economic shipping operations. A possible indicator of SEEMP, the EEOI is the mass of carbon dioxide per capacity-mile that the ship carried which displays the energy efficiency of a specific leg (or average number for the whole voyage or period) under different operation conditions. Capacity here is an expression of the actual carried amount of cargo, by tons, TEUs, cars, or other units. By tracking the fluctuation of EEOI, the effect of SEEMP implementation can be observed, assessed, and the LCS measures become possible to be applied and controlled to have better results in energy efficiency (IMO 2012). While SEEMP and EEOI are applied to the current world fleet, EEDI is a stricter and a more future-oriented measure, focuses on the ship designing and building phase and will be tightened every 5 years. Unlike the case of SEEMP which rather rely on the voluntary and commitments of the projected subjects, the compulsory integration of EEDI into the industry is not easy given the split incentives of stakeholders and the shortage of knowledge in this domain (Zheng et al. 2013). The critical role of EEDI and its incremental schedule in LCS progress are accentuated by the study by Hoffmann et al. (2012) in which they demonstrated a dominant 93% occupation in CO_2 reduction potential of new ships.

As stated in the resolution MEPC.213 (63) of the International Maritime Organization (IMO) Guidelines, SEEMP includes four primary components: planning, implementation, monitoring, and self-evaluation and improvement. In these stages, planning is recommended as the most crucial stage of the whole plan (IMO 2012). It affects both the CO_2 emission and energy efficiency level of shipping companies. LCS measures considered by ship owners or operators in this stage are both operational and technical. With EEDI, the consideration of LCS measures arises primarily in the design phase of a vessel with the choice of the shipowner or the designer/builder on behalf of him. Necessarily, LCS measures putting on the debate in this phase belong to a technical design aspect. In order to build up a project that involves multi-criteria decision-making (MCDM), a planning framework is critical. There are abundant of papers that introduce and show the research results in LCS measures (Bouman et al. 2017; Buhaug et al. 2009; Ge and Wang 2016; Psaraftis 2012; Rehmatulla et al. 2017; Smith et al. 2014; Wan et al. 2015; Wärtsilä 2016). However, a knowledge gap between the LCS methods and the implementation of shipowners still exists since IMO has solely issued guidelines for the implementation of SEEMP and leave the choice of technologies to the industry (Rojon and Smith 2014). Meanwhile, shipowners, operators, designers, and builders are being surrounded by a large number of available measures with their limited resources. Several questions could be raised about the decision-making structure in LCS technique selection: (1) What factors should the LCS decision-making process consider? (2) What information should be collected? (3) How to handle these pieces of information to make the final LCS decisions?

To solve these problems, it is crucial to build up a clear and rational MCDM procedure from collecting information to analyzation and summarization to make final decisions. Decision makers and stakeholders could find it hard to reliably identify, collect, and process a large database for this purpose. Given the current difficulties as well as the scarcity of an information-oriented framework for shipping companies to prioritize LCS measures and limit the effects of the Energy-Efficiency Gap (EEG), this study will propose a resolution pathway to fulfill the observed gap. To achieve this, a literature review in LCS is in Section 2. Then, the generic structure of the MCDM framework will be introduced in Section 3. Sections 4 and 5 will present the proposing framework in details. Discussions and recommendations on the application of the framework will be addressed in Section 6. Finally, Section 7 concludes this paper with limitations as well as future development direction.

2 Literature review

The marginal abatement costs and cost-effectiveness of energy-efficiency measures submitted by the Institute of Marine Engineering, Science and Technology (IMarEST) on 23 July 2010 identified and assessed the cost-effectiveness, technology maturity, applicability, and CO_2 abatement potential of numerous LCS measures (IMarEST 2010). A comprehensive and transparent methodology for conducting cost and efficiency analysis for each measure and another method for estimating the Marginal Abatement Cost Curve (MACC) is also proposed. However, this paper admitted that there were further works that needed to be done to provide the actual in-service cost, reliability, variability, and effectiveness of these measures. The third IMO GHG Study and the following simulation report indicated that without timely policies, the amount of CO_2 emission will rise (Smith et al. 2014, 2016). Wärtsilä (2009) published their Energy Efficiency catalog, which is updated in Wärtsilä (2013) and (2016) introduced examples of possible measures to reduce energy consumption in ship application but other means of LCS such as renewable energies or carbon storage have not been covered. The trend of research toward better technical measures of LCS is also observable according to the recent review study of Shi et al. (2018).

In other pieces of research by Buhaug et al. (2009), Eide and Endresen (2010), Dimopoulos and Kakalis (2014), UNCTAD (2009), Smith et al. (2014), and Faber et al.

(2009) assessed present and future emissions from maritime transport and introduced and categorized possibilities to reduce emissions. Other research which also considered energy efficiency and emissions in maritime transport are Ballou et al. (2008) with the investigation of the optimized speed for both fuel consumption and GHG emission analysis and Corbett et al. (2009) with optimizing fuel emission and service level. Bunker consumption and customer service level trade-off analyses were also investigated by Qi and Song (2012) and Brouer et al. (2013). Hu et al. (2014) proposed a manner to minimize fuel consumption and emissions of the vessels through berth and quay-crane allocation optimization. More practical and comprehensive solutions to third-party service providers such as Wärtsilä (2016) are also proposed. It is observed that by merely lowering operational speed, cases achieved fuel saving rates of up to 70% with container vessels and 50% with tankers (Mander 2017). However, in the long run, the conversion and transition from traditional energy resources to LCS fuel sources is preferable to using situational solutions such as fossil fuel with low operational speed (Smith et al. 2016). A comprehensive list of available and promising measures with updated information from various sources is introduced in Section 4.2.2.

The EEG is mentioned by Jafarzadeh and Utne (2014) and Johnson and Andersson (2014) as the inconsistency between cost-effective technologies and its actual implementation. This phenomenon is explained by the existence of barriers rooted in different aspects such as economic, organizational, and behavioral sciences. It is also indicated in this study that information and technology barriers, undoubtedly is one of the causes leading to misconception and inappropriate decision especially in energy efficiency measure implementation (Johnson and Andersson 2014). The study of Dewan et al. (2018) identified and categorized the barriers in the implementation of energy efficiency measures in shipping industry into seven groups: Information barriers, financial barriers, intra-organizational barriers, technological barriers, technical (know-how) barriers, policy barriers, and geographical barriers. The volatility between academia and practice is also expressed in the multi-objective decision support review of Mansouri et al. (2015) and to bridge this gap, this study suggests the development and implementation of the Decision Support Systems (DSS) powered by MCDM methodologies. Additionally, there is still a misconception that merely by apply measures, energy can be saved and bring back positive impacts (Jafarzadeh and Utne 2014). One of the most headache problems with the implementation of CO_2 abatement measures is the lack of reliability and immatureness. The cross-sectional survey of Rehmatulla et al. (2017) shows that while the few broadly implemented measures do not provide a significant abatement potential, more promising technologies with higher claimed performance have not been applied in a sufficient scale.

Maritime transportation is an industry that was built on complex systems. Numbers of research articles used MCDM techniques as the compass to achieve the target of a proper selection based on multi-objectives condition. Windeck (2013) attempted to minimize fuel consumption and GHG emissions through liner shipping network design using Mixed Integer Linear Programming (MILP). Celik and Cebi (2009) introduce the analytical Human Factors Analysis and Classification System (HFACS), based on a Fuzzy Analytical Hierarchy Process (FAHP) in order to identify the role of human errors in shipping accidents providing an analytical foundation and group decision-making ability. Kandakoglu et al. (2009) proposed a framework for shipping registry selection in maritime transportation industry under multi-criteria. While numerous studies target introducing specified algorithms and models for optimizing maritime operations, only limited ones propose generic DSSs to support the MCDM problem in maritime transportation (Mansouri et al. 2015). Mansouri et al. (2015) also observed that environmental sustainability is the sector that received the highest attention and there is a rising trend in applying multi-objective optimization to overcome different obstacles in maritime shipping. The study of Schinas and Stefanakos (2014) address a selecting problem with SO_x abatement technologies for MARPOL Annex VI compliance using AHP and analytic network process (ANP). An analyzation of the research approach and utilized methodologies in green port and shipping is presented in the study of Shi et al. (2018).

3 The generic structure of the MCDM framework to support SEEMP and EEDI planning

This framework is an attempt to bridge the gap between SEEMP, EEDI, and LCS measures application. As a result, a strong connection between them must be maintained. The selected measures should be the prioritized ones based on multiple criteria. From the view of a shipping company, economic advantages result from better energy efficiency is the primary motivation for LCS implementation. The recognition of the industry and society with the company image also explains the attention of the company toward its ecological performance. However, many LCS technologies are in their developing phase with early prototypes and trials. The related risks in the process of applying these measures to the existing fleet or their questionable performance on new ships is also a significant concern of stakeholders (Johnson and Andersson 2014).

The whole framework could be separated into three primary stages: (1) input database: information collection; (2) summarizing, analyzing, and decision-making (SADM); (3) output decision and data (Fig. 1). This framework is applicable to both planning new and operating vessels.

It is noteworthy that SEEMP and EEDI planning should be carried out in a ship-specific and enterprise-specific base (Smith et al. 2016). Therefore, factors that have major impacts on the LCS decisions should be designated and analyzed on an individual basis. Moreover, the resolution of IMO on the framework and structure of SEEMP stated that the planning stage should be taken with sufficient time so the most appropriate, effective, and implementable plan can be developed (IMO 2012). Consequently, an inclusive data set from multiple sources should be collected accordingly in the first stage of the framework. It is also designed to be compatible with a future situation that enterprises have to take in hand laws and regulations change in multiple layers (Fig. 1).

The main purpose of the SADM block is to handle data collected from the input block and put forth a prioritized list of LCS measures. As indicated by Wang and Nguyen (2016), one of the most important motivations for applying LCS measures is the improvement of energy efficiency. The economic returns from this are enough to encourage stakeholders to implement LCS solutions even before the pressure from the legal sector. However, there are several trade-off relationships that could be identified in this problem. An effective and comprehensive alternative in the ability of energy saving

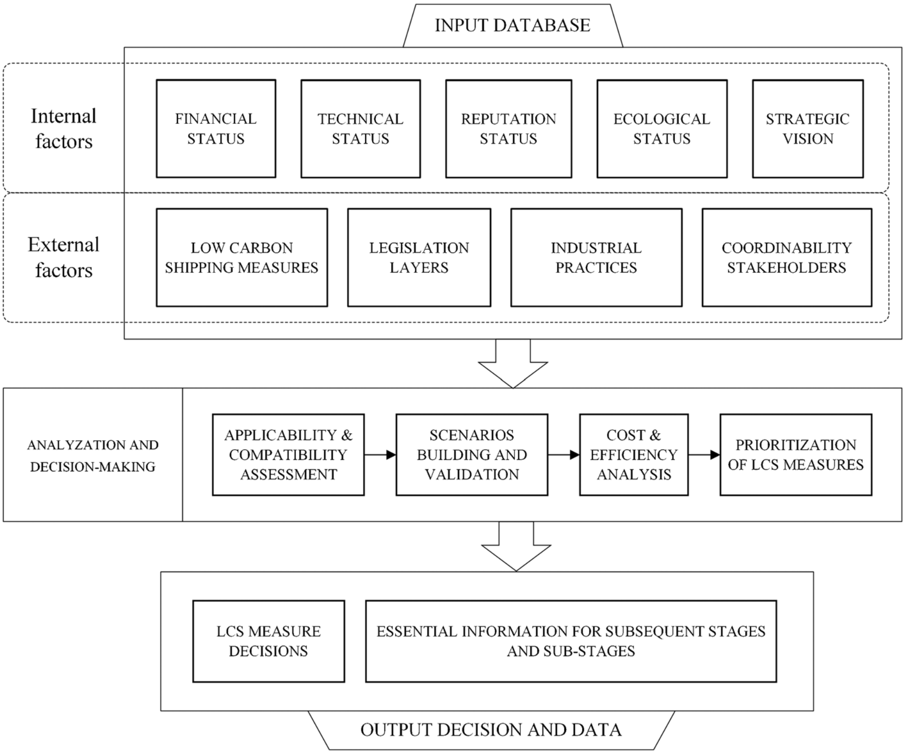

Fig. 1 The MCDM framework to support SEEMP and EEDI planning

could bring back significant and better ecological performance on ships and a possible promising cost reduction but will likely to have a deeper interference in the mechanical structure of the vessel or the existing operational schedule of the fleet, e.g., low-speed engine installation or speed reduction. On the other hand, there are new technologies that could substantially improve the company image or even depict it as a pioneer in R&D activities. This will trigger other following competitive advantages such as better capital mobilizing or freight reduction capacity. However, being on the edge is not a favorable stand of shipping companies (Rehmatulla and Smith 2015b). They will likely have to deal with related risks such as unstable operations or underperformance. The balance of these trade-offs also depends on the perspective and strategic vision of the company.

The expected most “suitable” solutions here could be understood as the LCS measures that provide the highest projected performance in reducing CO_2 emission or energy efficiency. Accordantly, have better effects on the competitive ability of the organization with higher certainty in implementation. The suitableness or the balance among criteria is reflected by the related perspective, vision, as well as strategies of the company. Recommended assessing criteria of LCS measure are described in Section 5.3. In practice, there are numerous LCS technologies and methods available in the industry and market through cooperation campaigns, R&D projects, and commercialized services. To tackle the problem of information overloading as well as prepare authentic materials for prioritizing and decision-making, two other sub-stages will be carried out: Applicability and compatibility checking and cost and efficiency analysis. The output of the prioritizing mechanism should be a prioritized list of LCS measures for the decision-making process. The structure of the framework encourages the setup of an inclusive input database and ensures the prioritizing process is ship-specific and enterprise-specific. As this framework is proposed in an open structure, it is customizable on its kernel to balance between performance and adaptation in actual implementation. Thus, different analysis techniques, or investment appraisal methods, etc., can be employed as a way to achieve the final results.

The output of framework is designed to be the decisions on the implementation of LCS measures for SEEMP and/or for acquiring compulsory EEDI level and other information which is essential for other stages and substages of SEEMP and operation and maintenance activities. However, the situations where the combinations of top-priority measures create intolerably uncertain aggregate effects are not scarce in practice. In that case, the output of this phase is not yet a final decision but only a prioritized list of measures that could be applied. This problem will be discussed further in Section 6. The other output is the established LCS and energy efficiency database that was summarized and analyzed carefully for each vessel in the fleet. Apparently, this will be useful for the implementation, monitoring, and self-evaluation stages.

4 Input database establishment—inclusive information collection

In the proposed framework, it is undeniable that the quality of the output will be absolutely affected by the input. The first stage is information collection and it should be carried out in the way of sufficiency and accurateness. Otherwise, deficiency in this stage will lead to undesired results such as low real performance or unstable in actual operating conditions. For example, the LCS measures information shortage may cause missing possible alternatives or misleading evaluation due to unrealistic basis. Misunderstanding or failure to identify the requirements of the laws and regulations might make the final results impractical. To assess the suitableness of different LCS measures in the next stage, information barriers must be noticed and avoided or eliminated. Information barriers are always mentioned as a significant point in EEG pieces of research but often being overlooked in improving shipping energy efficiency (Table 1). The information collector, as well as decision maker, should pay more attention to them for a more

Table 1 The information barriers encountered in improving shipping energy efficiency

Barriers level	Dimensions level	
Information	- The lack of information - Not using information - Information inaccuracy - Changes in human resource - Circumstances variations - Adverse selection - The overload of information	- Not maintaining information quality - Moral hazard and principal-agent relationships - Lack of interest in information investment - The improper form of information - Poor belief level in the source of information - Cultural differences regarding the required information

Source: adapted from Jafarzadeh and Utne (2014) and Johnson et al. (2014)

comprehensive and accurate database with the proper form of information (Jafarzadeh and Utne 2014; Johnson and Andersson 2014; Rehmatulla and Smith 2015b).

4.1 Internal data

A crucial part of the data collection comes from the inside of the shipping company, which mainly refer to the current financial, technical, reputational, and ecological status. By establishing a sufficiently complete awareness of the current situation, the derived results of the MCDM process will be better tailored for the company.

Financial status This is an important aspect of LCS projects. Even though it is completely different from returns from LCS investments, the accessibility to capital must be considered to ensure the possible application of LCS measures after they are chosen. It is also worth noting that despite the acceptable investment for a vessel, that of the whole fleet can become unbearable with the company (Jafarzadeh and Utne 2014). The budget for energy efficiency of a shipping company, in turn, is limited and largely depends on its related strategies and visions, even though calculations proved that the NPVs of these investments are positive (Wang and Nguyen 2016). This relationship could be observed in practice where shipping companies with stronger capital power have their significant advantage over smaller ones in LCS technologies R&D activities and implementation. Maersk Line with their triple E class container ships or recently, CMA CGM with the Megamax-24 container ships.

Fleet technological and operational status Individual vessel status must be considered, both in operational and technical aspects. For the compatibility checking in the next stage or LCS measures application process, technical information of each vessel in the fleet must be available (technical blueprints, applied technologies, retrofit history, recent operation logbooks, loading factor, ability to fit new equipment, opinions, and responses of onboard officers: captain, chief-engineer, etc.). In the case of EEDI, as the prioritization of LCS measures is intended to be in the design phase of new ships with the supervision and then sea trials verification of classification societies, the implemented measures are not retrofitted but integrated into the ship's structure initially. As a result, both operational and technological measures stand equally in this aspect for new ships. However, with existing vessels, the applicability of LCS measures, especially technical ones is more limited due to the fact that there are technologies that cannot be retrofitted into existing vessels or excessively intrusive (IMarEST 2010; Stevens et al. 2015). The installation and interference with fundamental parts of a ship, e.g., propulsion system, main or auxiliary engine, hull structure, etc., is significantly more complicated and seems to be hiding more risks than the case of EEDI on new ships. Here, operational measures are more feasible and certain in both implementation and maintaining. Hence, the condition of the vessel (size, type, and age) will affect the possibility of applying specific LCS measures on specific ship critically.

Reputation and competitive advantage status and related strategies of the company Both the stand of the company in the industrial and its related strategies are important regarding its view and assessment of possible LCS measures and their effects on the performance of the company. For example, a decision of applying a newer LCS technology to its fleet will likely have more positive impacts on the company image and even differentiate its services from others on the market. However, the negative effects of a lower technology maturity are normally lower certainty and reliability in the application and probably more expensive maintenance and repair activities (Buhaug et al. 2009; Rehmatulla and Smith 2015a; Wang and Nguyen 2016). The equilibrium in this situation is conceivably indicated by the standards of decision makers and judgments from experts. Further discussion regarding the effect of LCS measures decision in this aspect is in Section 5.3.

Fleet ecological status As the purpose of this framework, the current status of CO_2 emission from the fleet must be investigated, this can be expressed by the EEOI or average EEOI of the vessel which is explained in the second IMO GHG study by Buhaug et al. (2009). The form of information also depends on the regulations that applied or possibly be applied in the future (when this framework is used). EEDI is the first ever mandatory global greenhouse gas reduction regime for an international industry sector and it plays an important role in the ecological status of new ships (Rightship 2013). Another source of data is the Existing Vessel Design Index (EVDI) which has similarities with the EEDI design but working for the existing world fleet (Rightship 2013).

4.2 External data

There are two dimensions of the external data required for a comprehensive and effective MCDM process which are (1) related layers of laws and regulations and (2) peer practices and stakeholder coordination.

4.2.1 Related layers of law and regulation

National Until now, although CO_2 taxing and trading schemes are available in various countries, specific CO_2 regulatory regimes for maritime transport do not yet exist in national level. An overview of the situation could be obtained from the status report of the International Carbon Action Partnership (ICAP) (ICAP 2017). However, since there are still domestic maritime transport markets and the possibility of regulations applied on vessel arrival or departure from a regulated port in a country, the appearance of it is not inconceivable. Take the UK as an example, it is known for its active position, both in the implementation of measures and legislation to tackle carbon emissions from shipping. Its commitment of a path to reduce 80% by 2050 and a system of 5 years of "carbon budgets" in the UK's Climate Change Act (CCC 2011) or other leading edge climate change policies with mandatory mechanism (Gilbert et al. 2011) are pieces of evidence that prove the significance of seeking legislative writings in the national level. An act of making UK's unilateral actions in the adjustment of a national carbon budget or reducing UK's share of global carbon emissions also have been considered (Gilbert et al. 2011). Although these actions are considered to be deferred (UK Department of Energy and Climate Change 2012), an act in the national level regarding CO_2 regulatory regimes is clearly possible. For example, Canada, California, and China have implemented unilateral schemes of carbon pricing which could be expanded to shipping (ICS 2017).

Regional Regional regulations, if available, must be considered rigorously. Here, the endeavors of the European Union (EU) in general and European Commission (EC) in particular is unique and remarkable. EC has submitted its proposal for the regulation of the European Parliament and the European Council on the monitoring, reporting, and verification of carbon dioxide emissions from maritime transport in MRV regulation no. 525/2013 (European Commission 2013). This proposal is entered into force on 1 July 2015 and from 1 January 2018, shipping companies have to comply with the MRV process. This is also considered by the EC as the model for a global MRV system that could be facilitated by IMO (European Parliament 2015). Attentions toward significant economic incentives such as the Green Award or other environmental discounts as of Hamburg port (Nikolakaki 2012) also need to be paid in this legislation layer.

International This is the most general level of regulation related to LCS. With the devotion and leading of the IMO in producing a comprehensive package of technical regulation for reducing shipping's CO_2 emissions which is entered into force in January 2013. This includes two crucial points: (1) system of EEDI for new vessels; (2) a template for the SEEMP for use by all ships. Furthermore, other market-based measures (MBMs) are also in consideration even though there are still barriers to overcome (Koesler et al. 2015). This can be observed in the call for MBMs of IMO secretary-general Koji Sekimizu in February 2012 (IMO 2013) and the recommended solution submissions from the members of the Marine Environment Protection Committee (MEPC) (IMO 2011, 2013). In October 2016, a scheme for CO_2 emission data collection has been adopted by IMO members. This opens a chance for IMO to develop additional CO_2 reduction measures.

It also worth noticing here that the nationality of a vessel is in accordance with the registered country, it can be different with the physical location of the enterprise and likewise the countries of the ports of call. Ensuring the enterprise or the specific vessel position under regulations is critical. As a result, this information should be considered comprehensively to ensure the completion of the database.

4.2.2 Peers practices and stakeholder coordination

Learning from industry's best practice All theoretical solutions, even offered by trusted providers may have a variance in comparison with the realistic application. In addition, there are great chances that a wide-known failed report of an early installation, trial, or prototype will delay the implementation of a new technology or LCS solution (IMarEST 2010). Meanwhile, the availability of industrial application experiences will be helpful in assessing the pragmatic performance of LCS measures in actual operating situations. However, the updated quality of the considered practices is important here. The usefulness of collected information is deteriorated over time because of the advance speed of technology. Another obstacle is the scarcity of available up-to-date data of newest technologies which are narrowly or not yet applied in the industry. Therefore, the assessment of the maturity of an LCS technology largely depends on the assistance of experts, consulting organizations, and service providers in the field.

Considering the relationship and coordination between the company and other stakeholders The purpose of this data is to ensure the ability of the improvements in operation and harmonization in operational measures in the transportation or logistics chain; it will be one criterion which decides the availability for several measures in the stage of applicability and compatibility in the SADM block. A typical case is voyage optimizations, e.g., just-in-time arrivals (JITA), which is expected to have a 1–5% of energy saving depending on managerial factors such as contractual agreements, incentives, and penalties for inefficient port calls (Buhaug et al. 2009). Speed reduction in combination with immediate berthing unquestionably requires the transparency in information and the effective connection between the port and ship. The study of Parviainen et al. (2017) indicated that multiple stakeholders in multiple nodes and links of the shipping network could facilitate better performance on the corporate social responsibility (CSR). The recent model of Global Industry Alliance (GIA) with the participation and coordination of both public and private sectors in support of low-carbon shipping is an example.

LCS measures information Abatement options are divided into two major group: operational and technological. Unlike technological measures, operational ones do not require physical modifications to the ship and hence could be applied to a more extensive range of situations. Conversely, the universality in the application of technical measures is definitely lower even though the fact that several of them can be retrofitted. It is also worth noting that, SEEMP and EEDI are supposed to be individually oriented, which means each vessel should have their own SEEMP to implement and develop or EEDI to achieve (IMO 2012). With each LCS measure, essential criteria should be collected, analyzed, and assessed in an individual base. The first reason is the costs and return of LCS measure, i.e., its economic effect may vary significantly for ships of different age and condition. Additionally, there are LCS measures that cannot be implemented on a certain ship type, size, and age (IMarEST 2010). More than that, except with the case of building identical ships, both abatement potential and level of certainty are varied between vessels, treating them as one model will ravage the accuracy of the decision-making process.

Technical information Almost all LCS measures, especially by a technical design approach are efficient or technically available for specific types of ships (Wärtsilä 2009). Consequently, unavailable measures from this sub-stage will make more burdens for the next ones, this may lead to another type of information barrier: the overload of information (Jafarzadeh and Utne 2014) and a decrease of the performance of a whole decision-making process. As the focus of the framework is on LCS measures decision-making, the collected technical information requires interaction between shipowners and sources of information such as consultants, suppliers, service providers, or research institutions in a ship-specific basis. The data set in this sub-stage may include:

a) Abatement potential: It is clear that LCS measures are purpose-built tools for decreasing CO_2 emission and therefore the ecology aspect should be an essential criterion to evaluate the LCS measures. This aspect expresses the ability of a specific measure in decreasing CO_2 emission on a specific ship, in the form of CO_2 percentage decrease in the application (IMarEST 2010). This abatement potential data will also be used to judge the potential of a measure in reducing CO_2 emission to meet the strictest requirement of laws and regulations. It is usually in a range-form of value with maximum and minimum values due to its uncertainty. It is recommended by the study of Wang and Nguyen (2016) that fuzzy number is a useful tool to handle this type of data. For the accuracy of assessment as well as performance in the application, these statistics should be collected in a ship-particular manner with professional technical expertized supports.

b) Technology maturity: These pieces of information should be one of the inputs of prioritizing mechanism in the SADM stage. This factor explains the opportunity costs that the enterprise invest in the measure later instead and have a shorter payback time or greater benefit from it. Furthermore, shipowners usually do not want to deal with excessive technical risk (Sorrell et al. 2000) as a front-runner, unless this action brings back huge enough tangible or intangible benefits according to their environmental strategy. Therefore, a technology or measure assessed as more matured will have a lower risk level and higher certainty level concurrently (Dewan et al. 2018).

c) The ability of technology support by the government or industry: There will be advantages for the company if it decides to implement a technology promoted by governments or industrial bodies. It can be supported in capital investment, incentive interest bank loan, or technology and know-how support from the most advanced technology institutions (Wan et al. 2015). These benefits and a better company image might have contrary effects on the decision-making process in comparison with the technical risk of LCS measures.

d) Other technical information: Application process information; retrofit ability; interference with other technologies or main operations; available area for application on board the ship of LCS technologies such as wind, solar, or speed reduction; installation time; maintenance frequency; warranty policy; and others.

Application costs Include tangible cost such as initial installation cost, maintenance cost, training and recruitment cost, accessories cost, etc. which are usually provided by suppliers and/or service providers and intangible cost such as opportunity cost, restructuring logistic or supply chain cost. (Dewan et al. 2018). These will be the input of the cost-efficiency analysis in the next stage, which indicates an economic benefit from the application of LCS measures.

Total reduction potential of LCS measures combinations In the study of IMarEST (2010), there are two reasons that LCS measures should be first considered to exclude each other: (1) The complementary or overlapping effects of measures, i.e., reduce CO_2 emission by using a measure could affect the result achieved through other measures. (2) Practical reason, i.e., certain LCS measures cannot be applied at the same time. As a result, the collected results should be analyzed and alternatives as groups of LCS measures (if possible) should be available in the prioritization stage. Table 2 provides an overview of existing technologies and methods.

Table 2 Overview of available LCS measures and technologies

Measures	Abatement potential (%)	Availability (Y/N)	Industrial application	Retrofit ability (Y/N)	Payback time
Improve operational energy efficiency					
Speed reduction	19–70	Yes	Widely implemented	Yes	Not known
Voyage optimization	0.1–48	Yes	Widely implemented	Yes	Very short
Capacity optimization	5–50	Yes	Widely implemented	Yes	Very short
Ballast and trim optimization	0–10	Yes	Implemented	Yes	Very short
Efficiency of scale	< 4	Yes	Widely implemented	Yes	Very short
Weather routing	0.1–4	Yes	Implemented	Yes	Very short
Autopilot adjustment	0.5–3	Yes	Implemented	Yes	Very short
Improve energy awareness	0.1–20	Yes	Widely implemented	Yes	Very short
Propeller polishing	2–8	Yes	Widely implemented	Yes	Very short
Hull cleaning	1–10	Yes	Widely implemented	Yes	Very short
Cold ironing	3–10	Yes	Implemented	Yes	Not known
Suitable RPM of the engine	< 5	Yes	Implemented	Yes	Short
Automation system	< 10	Yes	Implemented	Yes	Very short
Power management	< 5	Yes	Implemented	Yes	Short
Decrease turnaround time in port	< 10	Yes	Widely implemented	Yes	Very short
Technical design					
Light-weight construction	0.1–22	Yes	Implemented	No	Very short
Optimum hull dimension	5–9	Yes	Implemented	No	Medium
Efficiency of scale	4–5	Yes	Implemented	No	Very short
Low-profile hull opening	< 5	Yes	Narrowly implemented	No	Very short
Aft waterline extension	< 7	Yes	Narrowly implemented	Yes	Very short
Hull coating	1–10	Yes	Widely implemented	Yes	Very short

Table 2 (continued)

Measures	Abatement potential (%)	Availability (Y/N)	Industrial application	Retrofit ability (Y/N)	Payback time
Covering hull opening	< 5	Yes	Implemented	Yes	Very short
Optimization water flow of hull opening	1–5	Yes	Implemented	Yes	Very short
Low-speed engine	20–70	Yes	Implemented	No	Medium
Skeg shape/trailing edge	< 2	Yes	Implemented	No	Very short
Optimal propeller-hull interaction	< 4	Yes	Narrowly implemented	No	Very short
Interceptor trim plates	< 4	Yes	Implemented	Yes	Very short
Ducktail waterline extension	3–7	Yes	Implemented	No	Very short
Air lubrication	1–15	Yes	Narrowly implemented	No	Short
Propeller-rudder combination	< 4	Yes	Implemented	Yes	Short
Propeller upgrade	0.5–3	Yes	Implemented	Yes	Medium
Propeller boss cap fins	1–4	Yes	Widely implemented	Yes	Very short
Propeller nozzle	< 5	Yes	Implemented	No	Short
Optimization of propeller blade	2	Yes	Widely implemented	Yes	Very short
Counter-rotating propeller	10–15	Yes	Implemented	No	Medium
Wing thruster	< 10	Yes	Implemented	No	Short
Pulling thruster	< 10	Yes	Implemented	No	Short
Common rail	< 1	Yes	Implemented	Yes	Short
Diesel-electric drive	< 20	Yes	Implemented	No	Short
Diesel-electric drive and diesel mechanical drive	< 4	Yes	Narrowly implemented	No	Medium
Main engine tuning	0.1–0.8	Yes	Implemented	Yes	Very short
Waste heat recovery (WHR)	1–20	Yes	Widely implemented	Yes	Short
Hybrid auxiliary power generation	2–45	Yes	Implemented	No	Very short
Low-energy lighting and energy-efficient appliances	0.1–0.8	Yes	Widely implemented	Yes	Short
Energy-efficient HVAC	< 5	Yes	Implemented	Yes	Not known

Table 2 (continued)

Measures	Abatement potential (%)	Availability (Y/N)	Industrial application	Retrofit ability (Y/N)	Payback time
Speed control of pumps and fans	0.2–1	Yes	Implemented	Yes	Medium
Scrubber	44–77	Yes	Implemented	Yes	Not known
Low loss power distribution	< 2	Yes	Implemented	No	Medium
Bulbous bow	≥ 10	Yes	Widely implemented	Yes	Very short
Shaft line arrangement	< 2	Yes	Narrowly implemented	No	Very short
Wärtsilä EnergoFlow	< 10	Yes	Implemented	Yes	Short
Improvement of superstructure	2–5	Yes	Implemented	No	Short
Alternative lower carbon emission fuels					
Nuclear power	No CO_2 emission	Yes	Rarely implemented	No	Not known
LNG fuel	5–30	Yes	Implemented	Yes	Short
Biofuels	25–84	Yes	Rarely implemented	Yes	Not known
Hydrogen	No CO_2 emission	Yes	Rarely implemented	No	Not known
Renewable energy					
Solar power	0.2–12	Yes	Narrowly implemented	Yes	Long
Towing kite	1–50	Yes	Narrowly implemented	Yes	Short
Wind engine	3.6–6.6	Yes	Narrowly implemented	Yes	Medium
Fuel cell	2–20	Yes	Rarely implemented	No	Not known
Wave energy	Not known	Not known	Narrowly implemented	Yes	Not known
Flettner-type rotors	< 30	Yes	Narrowly implemented	No	Medium
Using emission-capturing technologies					
Carbon capture and storage	10–20	No	Rarely implemented	No	Not known

This table adapted information from studies of Buhaug et al. (2009), Lloyd's List (2009), Wärtsilä (2009), Eide and Endresen (2010), Glykas et al. (2010), IMarEST (2010), Hansen et al. (2011), Bertram (2012), Royal Academy of Engineering (2013), Wärtsilä (2013), Gibbs et al. (2014), Lindstad et al. (2014), Zhou and Wang (2014), Ge and Wang (2016), Wärtsilä (2016), Bouman et al. (2017), and Rehmatulla et al. (2017).

The utilized scale for payback time is used based on the catalog of Wärtsilä (2009) which could be described as very short (< 1 year), short (> 1 to 5 years), medium (5 to 11 years), long (11 to < 15 years), and very long (> 15 years). It should be noted that this table is recommended to be used exclusively for overviewing due to the diversity of service providers and development level as well as the individual basis of technologies application situations.

5 Summarizing, analyzing, and decision-making process and derivation of outputs

This block is considered as the analyzing core of the framework where the collected database from the previous phase could be utilized to find the most suitable LCS measures with the current situation of the internal and external factors. This phase begins with a cross-processing of different data categories to test the applicability and compatibility of LCS measures. The economic aspect and financial feasibility of the remaining alternatives are examined by a cost and efficiency analysis and furtherly trim down the list of possible LCS options. Finally, a mechanism will prioritize the shortened list of alternatives to support the final decision-making process (Fig. 2).

5.1 Applicability and capability

This is the first step in the summarizing, analyzing, and decision-making (SADM) block. The purpose is to qualify and narrow down the field of LCS options to prevent an information-overloading barrier (Table 1). Here happen the interactions between separated collections of input-stage. In specific:

LCS technical information with laws and regulations To reject prohibited measures in accordance with policies at any level. For instance: nuclear-powered vessels is prohibited in certain ports or countries.

LCS technical information with fleet technical status To reject inapplicable LCS measures according to technical characteristics of the specific vessel (include retrofit ability).

LCS technical information with the coordination ability of stakeholders To reject inapplicable LCS measures due to the imperfect position of enterprises in the transportation chain. Several LCS measures (especially operational ones) require the cooperation between stakeholders and if they are out of the unilateral

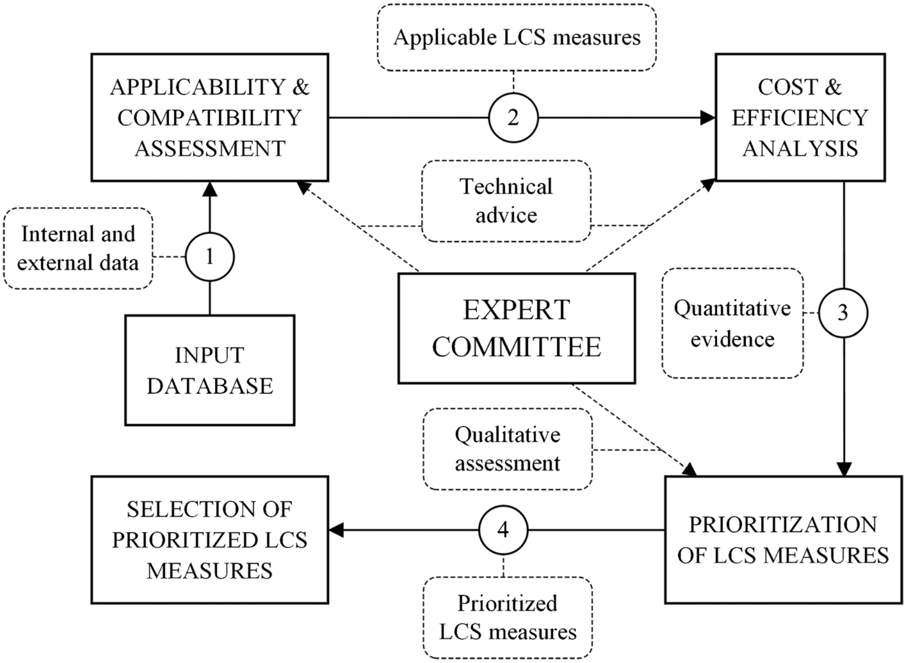

Fig. 2 Structure of the SADM block with four main steps

influence reach of the enterprise, it should be rejected and held back for being included in a proposal in group scale.

LCS measures with insufficient collected data With which do not have enough information to pass the uncertainty tolerance level of the enterprise or information requirements of the prioritizing mechanism should be rejected in this step to ensure the data handling ability of subsequent stages and accuracy of the decision-making process.

5.2 Cost and efficiency analysis

One of the most important criteria and also the main motivation in the LCS technologies consideration, from the view of shipping companies, is their actual efficiency in response to layers of law and regulations, and the financial result of the investment, i.e., quantifiable returns. The financial impacts of LCS measure application on the enterprise's need to be analyzed and assessed to continue narrowing down the field of available options and provide data for the stage of prioritizing mechanism. There are three primary results from this substage:

Investment appraisal From collected data, investments for each LCS measure will be evaluated. Among known methods (payback time, internal rate of return (IRR), net present value (NPV)), NPV is recommended for this purpose. The advantages of using

NPV is the comprehensiveness of using an information of capital, operational expenditures, fuel-saving ability, and the lifetime of investment to calculate the value of the proposed LCS measures taking into account the effect of discount rates. It ensures the simplicity but compactness of the model:

$$\mathrm{NPV} = R_0 + \sum_{t=1}^{T} \frac{R_t}{(1+i)^t} \tag{1}$$

where

R_0 is the initial investment ($t = 0$)
T is the lifetime of the investment
R_t is the net cashflow at time t
i is the discount rate

The lifetime of the investment in this case not only depends on the measure itself but also the status of the specific vessel and operating plan of the company. Next, R_t could be calculated as:

$$R_t = FS_t - Cap_t - Opr_t - Opp_t \tag{2}$$

where

Cap_t is the capital expenditure
Opr_t is the related operating cost
Opp_t is the opportunity cost, can be estimated through interest rate and/or cost of lost time and/or space due to the application of technology
FS_t is the value of fuel saving from the application of technology

Fuel saving (FS) can be calculated as:

$$\mathrm{FS}_t = \mathrm{FS}r \times \mathrm{OFC} \times \mathrm{FP}_t \tag{3}$$

where

FSr is the fuel-saving rate of the technology on the specific vessel
OFC is the original fuel consumption of the vessel
FP_t is the fuel price at time t

Reject LCS measures that surpass the budget or accessibility to capital If the initial cost or total tangible cost for applying LCS measure exceeds the ability of the enterprise, it should be rejected to avoid unnecessary further computation and consideration.

Reject LCS measures that have negative NPV (optional) As seen in Table 2, the majority of LCS measures have a positive payback time, it means that if lifetime T of the LCS investment is long enough, NPV value should be positive. Therefore, options with negative NPV should be rejected since they have negative effects on the financial status of the company. However, there is still a chance that pressures from the legal system are heavy enough to force the company to apply LCS technologies albeit their negative effects on the enterprise financial status.

5.3 LCS measures prioritization mechanism

5.3.1 Generic structure and the recommended prioritizing criteria

This part of the framework is crucial since it is directly related to the decisions of the stakeholders. The aim here is ranking different LCS measures based on multiple criteria. It should be noted here that the specialty of the company and its fleet are also considered in the process to ensure the suitableness of the list with a specific situation. The general structure can be described in Fig. 3:

Depends on the requirements of the enterprise about LCS measures (which should be included in the internal and external situations realized in the input block (Section 4)), criteria, and the corresponding database will be built accordingly. The database will be handled by a prioritizing mechanism, which is expressed in the form of algorithms. The requirements for the algorithm employed for prioritizing are the following: (1) able to handle multiple forms of input data and avoid losses of information in the process; (2) able to assess alternatives in a multi-criteria basis; (3) and able to capture vagueness and lack of information. Moreover, the simplicity and speed of the model are also important. In the study of IMarEST (2010), abatement options are ranked and then used to build up a MACC. However, several studies indicated that there are drawbacks of this method and its results have to be treated carefully due to the lack of uncertainty analysis (Heitmann and Peterson 2014; Kesicki and Ekins 2012; Kesicki and Strachan 2011).

Either considering technological or operational measures, application of an LCS one apparently has impacts on the company in multiple aspects. In fact, the relationship between the "environment" and "enterprise," both positive and negative has been argued since a long time ago (Claver et al. 2007; Schaltegger and Synnestvedt 2002). It is observable that the environmental performance of a company is primarily based on voluntary commitments and requirements. However, it is undeniable that the core of a company's business—the economic performance and its competitive advantage is becoming more and more affected by its environmental strategy-related decisions, not solely by stronger in contents and stricter in execution of laws and regulations but also by the possible benefits, both tangible and intangible when having a more advanced environmental management schemes (Claver et al. 2007; Lopez-Gamero et al. 2009). Claver et al. (2007) also indicated that an environmental strategy will definitely affect the firm's performance, which is later defined as a combination of environmental performance, competitive advantage, and economic performance. Lastly, the uncertainty connected with new technology applications in general and of LCS measures, in particular, have to be assessed carefully beside the mentioned factors.

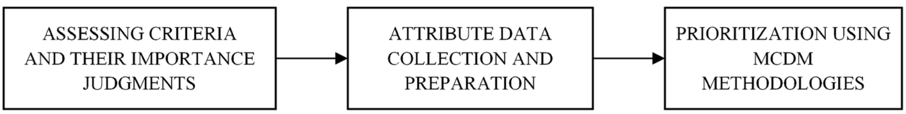

Fig. 3 Generic structure of the prioritizing mechanism

Therefore, we recommend four aspects as the main criteria for prioritizing LCS measures in this paper:

Ecology aspect As the technology for reduction of CO_2 as well as improve the energy efficiency level of ships, the ability of LCS measures in lowering carbon dioxide emission is definitely important. In addition, this capability is closely related to the economic effect returns from fuel saving which is one of the most obvious and tangible benefits of LCS to industrial stakeholders. With the compulsory character of EEDI, this aspect is also associated with the potential to make the EEDI of the designing ship meet the requirement and verification of classification society. This aspect could be presented by a percentage of the potential CO_2 reduce which is achievable by using the measure.

Reputation and competitive advantage aspect The impact of the specific LCS measure on the image of the enterprise. Implementing new environment-friendly technologies will probably differentiate the enterprise and improve its social performance (Mander 2017; Parviainen et al. 2017). Pioneering proactive strategy with new green technology also brings back positive results to the company's image and increased credibility in business relationships, i.e., reputation (Claver et al. 2007; Lopez-Gamero et al. 2009), more accessibility to capital or capital mobilization ability, and other advantages in comparison with other competitors (Lopez-Gamero et al. 2009). Pressure from cargo-owners and business partners is also observed as encouraging shipping stakeholders to invest in LCS technologies (Parviainen et al. 2017). Concerning the influence of applying LCS measures on both the financial status and competitive advantages of the company, this is definitely one of the decision criteria in prioritizing mechanism. The assessments of experts are recommended for this aspect due to its intangibility and generality in judging. A group of experts with their knowledge background and judging ability could use a standard predefined scale for the purpose of qualitatively describing the level of reputation and competitive advantage aspect gained by applying a new technology (Wang and Nguyen 2016).

Economic aspect Lower CO_2 emission does not necessarily mean better energy efficiency. In some cases, such as cold ironing, scrubber, or slow steaming, the actual effect of the technology on the energy efficiency and CO_2 abatement could be disparate from one another. In the case of cold ironing, it should be noted that this method only enables the use of greener sources of power from shore. While possibly releasing the pressure of emission from the ship, it does not promise a better ecological or economic performance. Meanwhile, slow steaming is apparently a good choice for saving energy. However, longer navigation time means negative effects on the supply chain and, to maintain the frequency of service and the bandwidth of the line, tonnage should be considered to be supplemented (Mander 2017). Even though this relationship is not always well-known, the core of a company is undeniably economic performance and application of new technologies definitely has effects on the company's monetary flow. In this aspect, LCS measures with the orientation of lowering the consumption of fuel have their significant advantage. The significant financial motivation from lower fuel consumption as well as other competitive advantages such as potential lower service production cost is also a stronger incentive than merely CSR. Consider LCS as investments with their initial, maintenance and repair costs, and returns are fuel savings, there are several possible measures for investment assessment appraisal which is discussed in Section 4.2.2.

Certainty aspect Consideration of applying new technology always is in line with the shortage of technical know-how, technical support, and risks in operation and maintenance. The certainty level in applying new technology also plays a critical role in decision-making. The report of Palmer and Smith (2017) indicated that reliability and scalability are considered by stakeholders as more important than the cost of the implementation. This concern makes sense because the calculated energy efficiency and financial return from the investment will be irrelevant if the performance of the technology is unstable. There is always a gap between academia and practice and the certainty level of a potential LCS measure has to be considered concurrently. A study by Stevens et al. (2015) indicated that the excessively low certainty is a barrier to the implementation of new green technologies. Uncertainty in adopting LCS measures can be found in several sections, e.g., abatement potential, bunker price, effects on ship operations and maintenance, etc., and this aspect should be rigorously analyzed in LCS measures assessment. This aspect also requires supports and judgments from experienced experts on the maturity of the technologies.

5.3.2 A preliminary MCDM method for prioritizing LCS alternatives

This study develops a generic MCDM framework for prioritization mechanism for LCS measures. As its mission, the mechanism is employed to resolve two derived problems: (1) finding the weight of criteria by which the LCS measures could be evaluated; (2) and prioritization of LCS measures based on weighted criteria. At the moment, there are potential tools that allow us to accomplish these tasks. Considering the trade-offs mentioned in Section 3 with both quantitative and qualitative criteria as recommended in Section 5.3.1, several descriptions could be drawn on the problem of prioritization.

Firstly, a definite number (m) of LCS measures will be considered as alternatives (A). They will be ranked based on their suitableness with the current situation of the company (internal and external) expressed by a set of n qualities denoted as C_1 to C_n and their importance denoted as w_i. The following equations illustrate the input database matrix I with d_{ij} are data points that contain performance ratings of each alternative in each criterion.

$$I = \begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_m \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & \cdots & C_n \end{array} \\ \begin{bmatrix} d_{11} & d_{12} & \cdots & d_{1n} \\ d_{21} & d_{22} & \cdots & d_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ d_{m1} & d_{m2} & \cdots & d_{mn} \end{bmatrix} \end{array} \tag{4}$$

$$W = \{w_1, w_2, \ldots, w_n\} \tag{5}$$

Secondly, for the purpose of ranking, the mode of comparisons could be either absolute or relative. However, the former is recommended by this paper to facilitate the transparency and better control of subjectivity in LCS measure assessment. A cardinal approach is also better in building a comprehensive database for further installation, maintenance, or other purposes in later SEEMP stages (IMO 2012). This, however, does not mean a denial of outranking methods such as ELECTRE (Roy 1991) or PROMETHEE (Brans et al. 1986). These methods are strong at handling the qualitative scale of assessment while taking into account the extents of imperfect knowledge of data (Figueira et al. 2013). Thirdly, it is noteworthy that the mentioned trade-offs in Section 3 are not directly related, i.e., the change to a different alternative which results in an increase of a criterion does not directly cause a corresponding decrease of another criterion. Moreover, the establishment of multiple objective functions seems to be unrealistic for a system that involves both quantitative evidence and qualitative assessment. Therefore, a multi-objective optimization approach (MMO) seems not certainly a rational approach here. A hybrid approach, on the other hand, is promising since the objects of ranking or scoring in problems 1 and 2 are different. For example, a pairwise and relative comparison manner such as an analytic hierarchy process (AHP) could be used for weighting assessing criteria while an individual-based method with the goal-inspired approach as a technique for order preference by similarity to ideal solution (TOPSIS) could be employed in combination. A suggestive model is described in Fig. 4 with five data entries is considered as prioritizing criteria and their relative weights as explained in Section 5.3.1 (Table 3).

While CAP and NPV could be provided or calculated based on quantitative data from different sources (see Section 5.2), CEL, ERC, and the perspective of the company on

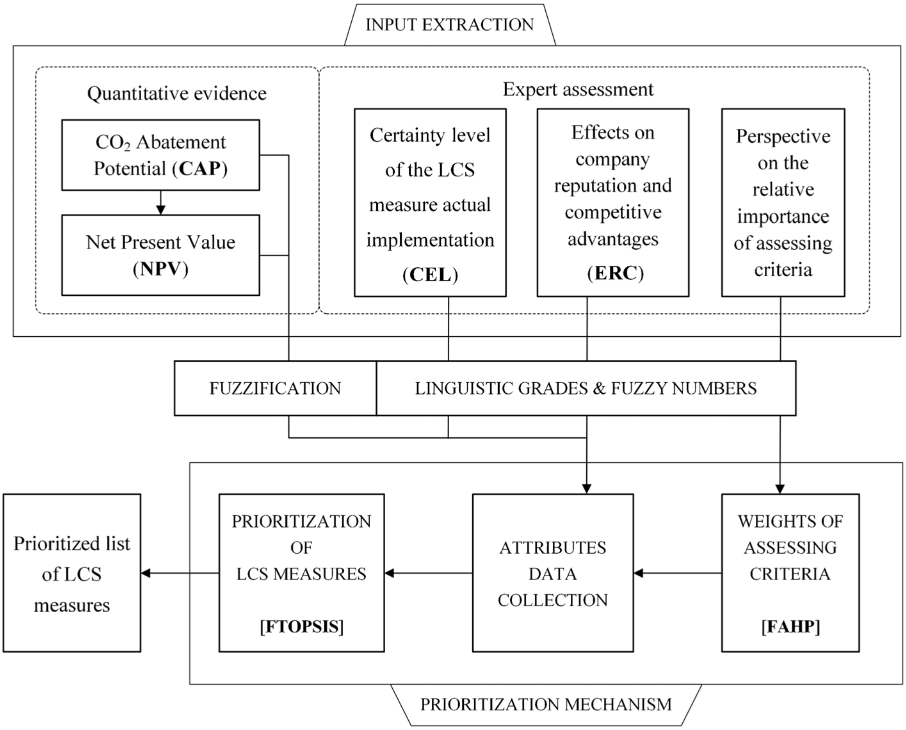

Fig. 4 A suggestive model for the LCS prioritizing mechanism

Table 3 Data entries used for LCS measures prioritization

Aspect of assessment	Utilized data	Unit or form of data	Components or sources of data
Ecological	CO_2 abatement potential (CAP)	Range of abatement percentage (%)	Service or technology provider, literature research, and advice from experts
Economic	Net present value (NPV)	Range of values calculated based on different scenarios	Calculated from expected scenarios of costs, returns, and the discount rate in the lifetime of the investment
Certainty in implementation	Expert assessments on the level of certainty (CEL)	Linguistic grades	Assessed by experts based on technology maturity, recent developments, industry application result, and ship condition
Effect on reputation and competitive advantages	Expert assessments on the expected effect on the company reputation and competitive advantages (ERC)	Linguistic grades	Assessed by experts based on the status of enterprises and expected effects of new technology application
The perspective of the company on different criteria	Expert assessments on the relative importance of assessing criteria	Linguistic grades	Assessed by experts based on the strategic vision of the company and possibly pressure from legal aspects

different assessing criteria are qualitative and should be derived from a carefully selected board of experts. A linguistic grade system with definitions and corresponding fuzzy numbers is recommended for the purpose of quantifying these data entries. The subjectivity stems from different perspectives could be controlled through the set of definitions for each linguistic variable. Considering each LCS measure as an investment project, there are uncertainties inherited from the non-deterministic nature of these alternatives in implementation. A well-known and effective apparatus to handle this problem is the fuzzy theory by Zadeh (1965). The data gathered of CAP and other related aspects such as fuel price, returns by better energy efficiency, or discount rate could be used to establish different scenarios, which will produce a range of calculated economic appraisal values and then later converted to fuzzy numbers.

A simple MCDM method with fuzzy-integrated such as FAHP is suitable with the assignment of quantifying the relative weights of assessing criteria (Saaty 2009). It allows faster and effective weighting with a small set of criteria, e.g., four in this model (Chen and Yang 2011). After all the required data are gathered, the Fuzzy-based TOPSIS (FTOPSIS), which is first introduced by Hwang and Yoon (1981) is utilized to rank the alternatives based on their distances to the fictitious ideal alternatives (both positive and negative), which are established as having all the "best" and the "worst" aspects of the alternative pool respectively (Roszkowska and Wachowicz 2015). The distance measuring and final defuzzification process could be carried out with multiple alpha cut-sets to deliver final, comparable values (Dat et al. 2015). There are also other approaches that could be suitable for this problem. For example, the study of Wang and Nguyen (2016) transforms the original purpose and utilized the Fuzzy Quality Function Deployment (FQFD) instead of FAHP as the criteria identifying and weighing method and the FTOPSIS as the prioritization apparatus. The study of Schinas and Stefanakos (2014) address a similar problem with SO_x using AHP and ANP.

5.4 Output—important derivative results and LCS measures selection

Based on the prioritized list of LCS measures, accessibility to capital, the strategy of enterprise, and other relevant factors, decisions of applying measures to limit the CO_2 emission can be made. Furthermore, the decision maker can build up a detailed plan for SEEMP implementation for both new and in-operation vessels (technologies or measure to be applied, their priority in the application, financial solutions, manpower, training process, etc.) with the information collected and analyzed in the process of applying the framework.

The output of the whole framework consists of (1) LCS measure decisions and (2) essential information for other stages and sub-stages in SEEMP as well as ship operation and management activities. The former is the primary target of the planning stage in SEEMP or the designing phase of a ship with EEDI. The latter includes information for implementation, monitoring, self-evaluation, and improvement stages such as training processes, application process, evaluation results of application, and monitoring.

6 Discussion

The offered framework has three vital points that potential users need to notice. Firstly, the power of the decision-making process in the proposed framework depends on the ability and effective resolution of the mentioned prioritizing mechanism. That factor is heavily affected by the mathematical decision-making techniques used in action. Meanwhile, the suitableness of the derived results also relies heavily on the quality and sufficiency of the information collected. Even if the methods in the SADM block are advanced and efficient, the shortage or inaccuracy of the database would significantly affect the usability of the results. Finally, the framework was constructed in an open manner that enables the sense of flexibility which allows its components to be modified to fit in various situations of companies and vessels.

Another noticeable problem is the aggregated effects of multiple measures into an LCS project. While the coordination of multiple measures usually enables better energy efficiency and CO_2 abatement, the uncertainty attached to the project, especially with relatively new combinations, is also increased. There are many cases in which the top prioritized LCS measures include technologies that are difficult to be utilized concurrently such as different alternative fuels or multiple solutions on a ship component, e.g., propeller or rudder. The CO_2 abatement ability and economic aspect of these combinations are also not necessarily additive. On the other hand, other LCS measures could be combined as a comprehensive project and their actual aggregated effect could be amplified by using them together such as propeller optimization with optimum hull design. In order to provide a better answer for this problem, an expanded structure for the SADM block is suggested in Fig. 5. After the prioritization of applicable LCS measures, a process of project building and validation could be implemented to develop feasible LCS combinations. The assessment and prioritization processes are carried out again to rank these alternatives and determine the most suitable LCS project to be applied. Although it sounds promising, the algorithm and mechanism of the project building and validation step still needs further investigations and specifications. Another concern is the consulting ability of the expert committee and necessary support such as technical simulation software in giving advice and qualitative assessments for individual projects, which is now becoming more complex than LCS measures in their individual form. The study of Ge and Wang (2016) proved the possibility of such an analysis. In practice, such

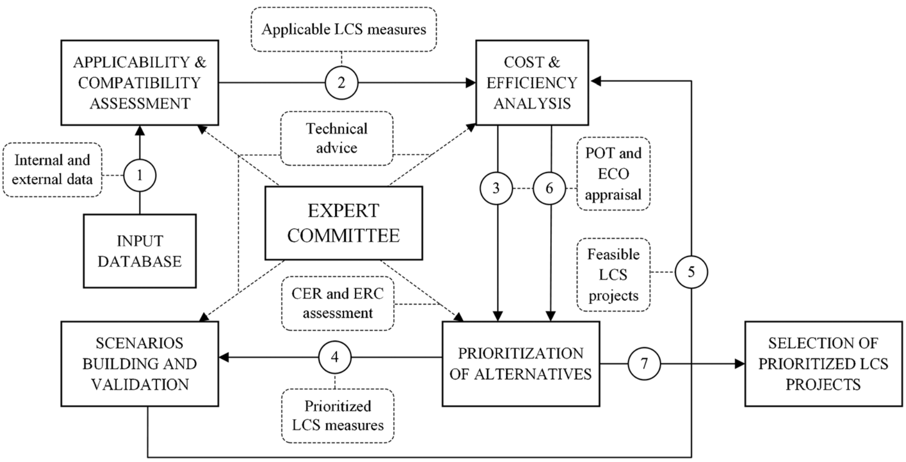

Fig. 5 The expanded SADM block with the consideration of LCS measure combinations

Table 4 Pseudocodes for the recommended FAHP-FTOPSIS method

1. Raw LCS measures and lists of related checks

```
LCS = {m_i | i = 1 → n};
exclude.m_i = {m_j | m_j cannot be combined with m_i};
retrofitability.m_i = "Yes" or "No";
abatement.m_i ∈ (0, 100];
NPV.m_i = NPV calculation (m_i);
```

2. Check for objective target (case of using)

```
If target = existing ship (retrofit) then
    For k = 1 : n
        If retrofitability.m_k = "No" then
            LCS = LCS – {m_k};
        End If;
    End For;
End If;
```

3. Check for Applicability and Capability

```
For k = 1 : n
    If (legal check (m_k) OR technical check (m_k) OR operational check (m_k) OR financial check (m_k) OR informational check (m_k)) = "True" then
            LCS = LCS – {m_k};
    End If;
End For;

Num = size(LCS);
```

4. Prioritizing individual measures

```
For k = 1 : 4
    Weightdata(k) = Fuzzification (inputs from experts, linguistic scale);
End For;
Criteria weights = FAHP (Weightdata);

For k = 1 : Num
    certainty.m_k = Fuzzification (inputs from experts, linguistic scale);
    Certainty(k) = certainty.m_k;
    competitive. m_k = Fuzzification (inputs from experts, linguistic scale);
    Competitive(k) = certainty.m_k;
    Abatement(k) = Fuzzification (abatement.m_k);
    NPV(k) = Fuzzification (NPV.m_k);
End For;

Priority = FTOPSIS (Certainty, Competitive, Abatement, NPV, Criteria weights);

If Num > Overload threshold then
    LCS = Selection (LCS, Priority)
End If;
```

5. Combinations finding

```
Combi={}; Temp={}; j = 1;
For i = 2 : Num
  combinable.m_i = LCS – (LCS ∩ exclude.m_i);
  While j ≤ size(combinable.m_i)
    If (Conflict (Temp+{m_j}) AND Over Budget (Temp+{m_j})) = "False" then
      Temp = Temp + {m_j};
    End If;
    j = j+1;
  End While;
  Combi = Combi + Temp;
End For;
LCS = LCS + Combi; Num = size(LCS);
```

6. Reassess available alternatives

```
LCS failed={};
For k = 1 : Num
    If Reassess (LCS(k)) = "Failed" then
        LCS failed = LCS failed + LCS(k)
    End If;
    LCS = LCS - LCS failed;
    certainty.LCS(k) = Fuzzification (inputs from experts, linguistic scale);
    competitive.LCS(k) = Fuzzification (inputs from experts, linguistic scale);
    abatement.LCS(k) = Reassess (Sum (abatement.m_i | m_i ∈ LCS(k)));
    NPV.LCS(k) = NPV calculation (LCS(k), abatement.LCS(k));
End For;
```

7. Prioritizing LCS projects

```
For k = 1 : Num
    Certainty(k) = certainty.LCS(k);
    Competitive(k) = competitive.LCS(k);
    Abatement(k) = Fuzzification (abatement.LCS(k));
    NPV(k) = Fuzzification (NPV. LCS(k));
End For;

Priority = FTOPSIS (Certainty, Competitive, Abatement, NPV, Criteria weights);
```

comprehensive projects normally need deep technical support and even life cycle service (Wärtsilä 2013). The deliberative platform for experts in working on the method of deliberation and also the aggregating manner of the extracted judgments such as Delphi or deliberative polling is also an interesting research direction in this field.

It should be noted here that the actual applicable LCS measures after checking steps should be low. An example provided by Wang and Nguyen (2016) has six final alternatives in a retrofitting case. However, the case of planning and calculation for new ships might be more complicated if there is an excessive number of available options. A selection of prioritized LCS measures should be carried out to limit the number of possible combinations (Section 4, Table 4). The individual measures should also be considered as alternatives in the final prioritization process since they usually yield a significantly better level of certainty than the combined options. Pseudocodes for the recommended FAHP-FTOPSIS method are shown below (Table 4):

7 Conclusions

This paper proposed a planning-support framework for shipping companies in their path to approach a higher energy efficiency and appropriate decision-making process in SEEMP as well as LCS measures selection. This information-oriented framework attempted to provide a procedure to collect, summarize, and analyze data comprehensively for the prioritization of various available LCS technologies in the market. The collected database including both internal and external situation as well as advice and assessments from experts could also be utilized throughout the SEEMP implementation process. The applicability and compatibility checking process was handled based on the interactions of information controlled by the decision maker. The framework structure was also built considering the information barriers to ensure an efficient performance of the proposed framework while avoiding unnecessary pressure and workload on the information processing system. A categorizing scheme for data collection has been introduced together with screening processes and recommendations for a prioritizing mechanism. Effective application of this framework could reduce not only the CO_2 emission but also increase the energy efficiency of the fleet.

Although the introduced framework attempted to make a bridge from the promulgation of SEEMP and its actual implementation performance, there are still limitations. First, the application of the proposed framework in actual situations for pragmatic validation is still not yet carried out in this study. The main obstacle here is the limited accessibility to necessary elements such as a specific ship or ship plan as the subject of LCS projects and collaboration or availability of reliable experts on this relatively new field. Even though an illustrative example has been introduced in the study of Wang and Nguyen (2016), further application and performance benchmarking of this generic framework should still need to be carried out to prove its feasibility and reliability for industrial confidence. Second, the specific method of the prioritizing mechanism and decision-making sub-stages such as the expert deliberative working platform remain unspecified. With the discussed model extension of the SADM block in Section 6, the key here might be the missing of a project building mechanism for LCS project with multiple combined measures. For future research direction, these missing pieces could be filled and the recommended method as the preliminary method in Section 5.3.2 could be actualized in a case study to establish a firm ground for reliability in practicability.

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