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Development of an MCDM framework to facilitate low carbon shipping technology application

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ABSTRACT

The aim of 40% CO_2 emission reduction by 2030 of the shipping industry has been adopted by the International Maritime Organization (IMO). The Ship Energy Efficiency Management Plan (SEEMP) and Energy Efficiency Design Index (EEDI) has become mandatory and served as a guidance for companies in low carbon shipping (LCS). However, the proactive implementation of LCS measures by stakeholders is still undeniably playing a decisive role. Unfortunately, a knowledge gap remains as the manner by which decisions regarding the selection and application of LCS measures can be made appropriately considering multiple criteria. In this paper, we analyze the primary internal and external factors influencing the LCS decisions and propose a problem – solving framework for shipping companies in choosing the most suitable LCS measures for individual ships to implement in diversified conditions. The framework has a generic structure thus researchers, policy makers, and decision-makers can apply it flexibly and diversely.

1. Introduction

Maritime transport contributes approximately 3% of global CO_2 emissions (Buhaug et al., 2009; Dalsøren et al., 2009; Endresen, Eide, Dalsøren, Isaksen, & Sørgård, 2008). The fact that bunker cost often represents around 60-70% of general vessels voyage costs can be observed from practice (Branch & Robarts, 2014; Stopford, 2009; Transparency Market Research, 2014). This is an important motivation for the trend of low carbon shipping (LCS) i.e. lowering the emission of CO_2 from shipping sector. The cost-effective method approach of Hoffmann, Eide, and Endresen (2012) displayed an auspicious CO_2 curbing potential of 30% and 53% CO_2 decrease with measure-by-measure and set of measures model respectively by 2030. With the adoption of the Ship Energy Efficiency Management Plan (SEEMP) and the Energy Efficiency Design Index (EEDI), shipping companies are having a great opportunity to achieve both financial performance and environment friendliness

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through LCS.

With the higher environmental awareness of the industry, ship designers, builders, operators and owners are now coping with progressively tougher new environmental framework. Currently, EEDI is considered as the most important technical instrument to reduce the CO_2 emission from the world fleet by setting a base line for energy efficiency of new ships. As long as the required criteria is attained, ship designers/builders are free to use the most cost-effective LCS plan to apply on their blueprints. The calculation of EEDI is explained thoroughly in the Resolution MEPC.212(63) of the Marine environment protection committee.

The SEEMP established a mechanism to urge the shipowners and operators to consider new LCS technologies and practices in ship operations, embrace the bright side of applying energy efficient measures to achieve both greener and more economic shipping operations. A possible indicator of SEEMP is the Energy Efficiency Operational Indicator (EEOI), which displays the energy efficiency of a specific leg (or average number for the whole voyage or period) under different operation conditions.

While SEEMP and EEOI are applied on the world existing fleet, EEDI is a stricter and more future-oriented measure. It focuses on the ship designing and building phase and will be tightened every five years. Unlike the case of SEEMP which rather relies on the voluntary and commitments of the projected subjects, the EEDI integration is compulsory. This is more difficult to achieve given the split incentives of stakeholders and the shortage of knowledge in this domain (Zheng, Hu, & Dai, 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 demonstrated a dominant occupation in CO_2 reduction potential of new ships (93%).

The SEEMP includes Planning, Implementation, Monitoring, Self-evaluation and Improvement. In these stages, Planning is recommended as the most crucial stage of the whole plan (IMO, 2012). It affects not only the reducing CO_2 emission capacity but also the energy efficiency level of shipping companies. LCS measures considered by shipowners or operators at this stage include both operational and technical. With EEDI, the consideration of LCS measures arise 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 consideration in this phase belong to the technical design aspect. To build up a plan, especially which involve multi-criteria decision-making (MCDM), a problem-solving framework is critical. Technical research results such as retrofit ability, abatement potential or measured performance of LCS measures are introduced and analyzed widely in literature. However, a knowledge gap between the LCS technologies or means and the implementation of ship-owners still exists since International Maritime Organization (IMO) has solely issued guidelines for implementation of SEEMP or EEDI and leave the choice of technologies to the industry (Rojon & Smith, 2014). Meanwhile, ship-owners, operators, designers and builders are being surrounded by large number of available measures with their limited resources. Several questions could be raised about decision making structure in technique selection:

(1) What are the influencing factors of the LCS decision making process?

(2) What information should the MCDM database includes?

(3) How to manipulate the database to support solving the MCDM problem?

Bearing in mind the difficulties of decision makers, stakeholders and the scarcity of a framework for shipping companies to identify, build-up database and rank LCS measures. This study will propose a resolution pathway to fulfil the observed gap and develop a decision-making framework to support SEEMP and EEDI planning. To achieve this, an LCS literature review is in chapter 2. Then, the structure of the framework will be introduced in chapter 3. Chapter 4 and 5 will present the proposing framework in detail. Discussions and recommendations on the application of the framework will be addressed in chapter 6. Finally, chapter 7 concludes this paper with limitations as well as future development direction.

2. Literature review

The Institute of Marine Engineering, Science and Technology (IMarEST) published the marginal abatement costs and cost-effectiveness of energy-efficiency measures on 23rd July 2010. The report identified and assessed the cost effectiveness, technology maturity, applicability and CO2 abatement potential of numerous LCS measures (IMarEST, 2010). A comprehensive and transparent methodology for conducting cost-effectiveness analysis as well as another method for estimating the Marginal Abatement Cost Curve (MACC) are proposed. However, this paper also admits that further, more in-depth analyses need to be done to provide the actual in-service cost, reliability, variability and effectiveness of these measures. Wärtsilä (2009) published their Energy Efficiency Catalogue, introduced examples of practical measures to reduce energy consumption in ship application. However, other means of LCS such as renewable energies or carbon storage have not been covered. In other pieces of research by Buhaug et al. (2009) (The second IMO GHG study), Eide and Endresen (2010), Dimopoulos and Kakalis (2014), UNCTAD (2009), and Faber et al. (2009) assessed present and future emissions from maritime transport, introduced and categorized possibilities to reduce emissions. Other research which also considered energy efficiency and emissions in maritime transport are Ballou, Chen, and Horner (2008) with the investigation of the optimized speed for both fuel consumption and GHG emission analysis, Corbett, Wang, and Winebrake (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, Dirksen, Pisinger, Plum, and Vaaben (2013). Hu et al. (2014) proposed a manner to minimize fuel consumption and emissions of the vessels through berth and quay-crane allocation optimization. A comprehensive list of available and promising measures with information from various sources is introduced in the Section 4.2.2.

The Energy Efficiency Gap (EEG) is mentioned by Jafarzadeh and Utne (2014) as the inconsistency between cost-effective technologies and its actual implementation. This phenomenon is explained by the existence of barriers rooted in various aspects such as: economic, organizational, behavioral sciences. It is also indicated in this study that information and technology barriers, undoubtedly are the causes leading to misconception and inappropriate decision especially in energy efficiency measure implementation. Additionally, there is still a misconception shared by many stakeholders that merely by applying measures, energy could be saved and positive impacts could be achieved (Jafarzadeh & Utne, 2014). There are obviously other uncertain factors that could undermine the effectiveness of the LCS application project, financially or technically such as instability of operation or underperformance in abatement rate. The delays and discrepancies between academia proposals and reality practices are also expressed in the Multi-objective decision support review of Mansouri, Lee, and Aluko (2015) and to bridge this gap, the study suggested the development and implementation of Decision Support Systems (DSS).

Maritime transport is an industry that comprises complex systems. Numbers of research articles used MCDM techniques as the compass to achieve the target of proper selection based on multi-objectives condition. Windeck (2013) attempted to minimize fuel consumption and Green House Gas (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, Celik, and Akgun (2009) proposed a framework for shipping registry selection in maritime transportation industry under multi criteria. While numerous studies target at 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 raising trend in applying Multi Objective Optimization to overcome different obstacles in maritime shipping.

3. A multi-aspect framework to support the LCS decision-making process

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 optimized ones based on multiple objectives. The framework is separated into 3 stages: (1) Input: Information collection; (2) Summarizing, analyzing and decision-making (SADM); (3) Output and the information current flows (Figure 1). This framework is applicable for both planning new and operating vessels.

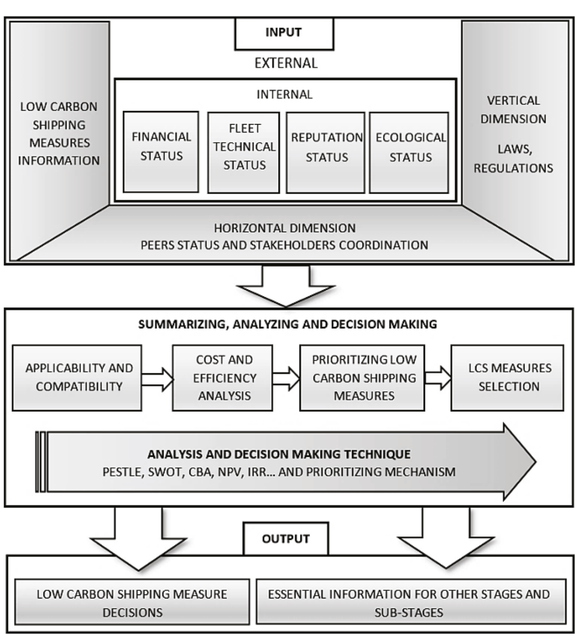

Fig. 1. MCDM framework to support SEEMP and EEDI planning

It is note-worthy that SEEMP and EEDI planning should be carried out in a ship-specific and enterprise-specific base. Therefore, factors which have major impacts on the LCS decisions should be designated and analyzed. Moreover, the resolution of IMO on framework and structure of SEEMP stated in the guidelines (IMO, 2012), suggest that the Planning stage should be taken with sufficient time so that the most appropriate, effective and implementable plan can be developed. Consequently, a data set includes multiple aspect sources should be collected accordingly in the first stage of the built framework. It is also designed to be compatible with future situation that enterprises have to take in hand laws and regulations changes in multiple levels (Figure 1).

The main purpose of Summarizing, Analyzing and Decision Making (SADM) block is to handle data collected from Input block and put forth LCS measures decisions. To tackle the problem of information overloading as well as prepare authentic material for prioritizing and decision making, two other sub-stages will be carried out: Applicability & Compatibility and Cost & Efficiency analysis. The output of the prioritizing mechanism is a prioritized list of LCS measures for decision making process. This structure also ensures the input for prioritizing mechanism is based on ship-specific and enterprise-specific data. As this framework is proposed in an open structure, it can be customized but remain 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 result.

The output of framework is 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 sub stages of SEEMP and operation and maintenance activities. The set of information in our framework, which is summarized and analyzed carefully for each vessel in the fleet will be useful in Implementation, Monitoring and Self-evaluation stages.

4. Input preparation – Comprehensive information collecting

It is undeniable that the input will absolutely affect the quality of the output. The first stage of the framework is information collection and it should be carried out in the way of sufficiency and accurateness. In opposite, deficiency in this stage will lead to low-performance or failure of the framework. For example, while the LCS measures information shortage may cause missing possible alternatives or misleading evaluation due to unrealistic basis, misunderstanding or fail to identify the requirements of laws and regulations will make the conclusive results impractical. To assess the suitableness of different LCS measures in the next stage, information barriers must be noticed and avoided or eliminated. Jafarzadeh and Utne (2014) indicate in their framework to overcome the EEG that there are information barriers in improving shipping energy efficiency and the information collector as well as decision maker should pay more attention on them to complete the database with accuracy and proper form of information.

4.1. *Interior data*

A crucial part of the data collection comes from inside the shipping company, which mainly prefer 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: Applying LCS technologies currently requires different types company resources such as personnel, financial, intellectual, or infrastructure. A widespread manner to mobilize and manage these resources with proper utilization for the final objectives is considering them as investment projects (Wang & Nguyen, 2016). Financial is one of the most important aspects for LCS projects. Even though there might be valid choices, limited accessibility to capital at the beginning phases of the application process could make the LCS technologies unfeasible. 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 & Utne, 2014). A rational budget should be prepared at this phase and revise later when the costs of LCS technologies are available.

- Fleet technological and operational status: Individual vessel status should be collected, both in operational and technical aspects. For compatibility checking in the next stage or LCS measures application process, technical information of each vessel in the fleet must be available such as technical blue-prints, applied technologies, retrofit history, recent operation log book, loading factor, ability to fit new equipment, opinions, and responses of on-board officers. In the case of EEDI, as the prioritization of LCS measures is intended to be in the design phase of new ship 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 factor for new ships. However, with aged 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 (IMarEST, 2010; Stevens, Sys, Vanelslander, & van Hassel, 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 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 a specific LCS measures on specific ship critically.

- Reputation and competitive advantage status and related strategies of company: Both the company's stand in the industrial and its related strategies are important regarding its view and assessment on possible LCS measures and their effects on the performance of the company. For example: An enterprise decision of applying a newer LCS technology on its fleet will likely to have more positive impacts on its image and even differentiate its services from other on the market. However, the negative effects are normally lower certainty and reliability in application and probably more expensive in maintenance and repair activities. The equilibrium of the balance in this situation is conceivably indicated by the standards of decision makers and judgements from experts. Questions could be raised in this aspect include: How important is the company/brand image in comparison with other performance indicators such as financial or service quality? The beneficial margin for the company's reputation is another crucial aspect. 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). 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, another source of data is Existing Vessel Design Index (EVDI) which has similarities with the EEDI but working for the existing world fleet (Rightship, 2013). The availability of this data will help the decision makers in determining the company demand of CO_2 reduction. Calculation tool and database services are now provided by various sources such as IMO, International Association of Independent Tanker Owners (INTERTANKO), or classification society such as DNV or ClassNK.

4.2. *Exterior data*

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

4.2.1. Horizontal dimension - Law and Regulation

- National: Until now, specific CO2 regulatory regimes for maritime transport do not yet exist in national level. However, since there are still domestic maritime transport markets and the possibility of regulations applied on vessel arrival or departure from regulated port in a country, its prospective possibility is still conceivable. This practice could be widely observed in the case of SO_x. Take United Kingdom (UK) as an example, UK is known for its active position, both in 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 five years "carbon budgets" in the UK's Climate Change Act (CCC, 2011) or other leading edge climate change policies with mandatory mechanism (Gilbert, Bows, & Anderson, 2011) is pieces of evidence that prove the significance of seeking legislative writings in national level. An act of making UK's unilateral actions in adjustment of 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 national level regarding CO_2 regulatory regimes is clearly possible. For example, Canada, California, and China have implemented unilateral scheme of carbon pricing which could be expanded to shipping (ICS, 2017)
- Regional: Regional regulations (if available) must be considered rigorously. The endeavors of European Union (EU) in general and European Commission (EC) in particular is unique and remarkable until now as EC submitted their 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 No 525/2013 Monitoring, Reporting, Verification (MRV) Regulation (European Commission, 2013). This proposal is entered into force on 1st of July 2015 and from 1st of 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).

- International: This is the most general level of regulation related to LCS. With the devotion and leading of the IMO in producing comprehensive package of technical regulation for reducing shipping's

CO_2 emissions which is entered into force in January 2013. This includes 2 crucial points: (1) System of EEDI for new vessels; (2) A template for the SEEMP for use by all ships. Furthermore, other Market-Based Instruments or Market-Based Measures (MBMs) are also in consideration even though there are still barriers to overcome (Koesler, Achtnicht, & Köhler, 2015) which can be observed in the call for MBMs of IMO secretary-general Koji Sekimizu in February 2012 (IMO, 2013) and submitted MBMs from members to 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 is recommended by the International Chamber of Shipping (ICS) that a resolution adopted by IMO must apply to all member states equally even though there are differences in responsibility between developing and richer countries according to the Paris Agreement. The reasons here are to ensure a level market and avoid "carbon leakage" (ICS, 2017).

It also worth noticing here, 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 port of calls. 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. Vertical dimension – Peers practices and stakeholder coordination

- Learning from industry's best practice: All theoretically information, even collected from trusted providers will always have variance in comparison with realistic application. In addition, there are great chances that a wide-known failed report of an early installation (even alpha versions or prototypes) will delay implementation of that technology or measure (IMarEST, 2010). Industrial application experiences, if available, will be helpful in assessing real performance of LCS measures in actual situations. However, the older the practices are, the poorer their value is. The main reason for this deterioration of information is the technological advances in the shipping industry are appearing faster and faster nowadays. This data is also not available with newest technologies which are not yet applied before in the industry.
- Considering the relationship and coordination between company and other stakeholders: The purpose of this data is to ensure the ability of 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 around 1% of energy saving (Buhaug et al., 2009). Speed reduction in combination with immediate berthing, unquestionably requires the transparency in information and the effective connection between port and ship. Assessment on the prospect of collaborations and agreements among related parties is crucial in the applicability of many operational and managerial LCS measures.
- 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 apply on a more extensive range of situations. Conversely, the universality in 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 is 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 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 vary between vessels, treating them as one model will ravage the accuracy of the decision-making process. Table 1 is built by the author with adopted information from studies of Bertram (2012); Buhaug et al. (2009); "Crew training is key to better ship efficiency" 2009); Eide and Endresen (2010); Gibbs, Rigot-Muller, Mangan, and Lalwani (2014); Glykas, Papaioannou, and Perissakis (2010); Hansen, Dinham-Peren, and Nojiri (2011); IMarEST (2010); Lindstad, Sandaas, and Steen (2014); Royal Academy of Engineering (2013); Wärtsilä (2009); Zhou and Wang (2014) . The utilized scale for payback time is used based on the catalogue of Wärtsilä (2009) which is Very short for <1 year and Very long for >15 years. It should be noted that this table is exclusively for overview purpose due to the varsity and the individual basis of technologies application situations.

Table 1
Available LCS measures and technologies

Measures	Abatement potential (%)	Industrial application	Retrofit ability (Y/N)	Payback time
Improve energy efficiency operational				
Speed reduction	19 – 23	Widely implemented	Yes	Not known
Voyage optimization	0 – 10	Implemented	Yes	Very short
Ballast and trim optimization	< 5	Implemented	Yes	Very short
Efficiency of scale	< 4	Widely implemented	Yes	Very short
Weather routing	0.1 – 4	Implemented	Yes	Very short
Autopilot adjustment	0.5 – 3	Implemented	Yes	Very short
Improve energy awareness	0.1 – 20	Widely implemented	Yes	Very short
Propeller polishing	2 – 8	Widely implemented	Yes	Very short
Hull cleaning	1 – 10	Widely implemented	Yes	Very short
Cold ironing	Not known	Implemented	Yes	Not known
Suitable RPM of engine	< 5	Implemented	Yes	Short
Automation system	< 10	Implemented	Yes	Very short
Power management	< 5	Implemented	Yes	Short
Decrease turnaround time in port	< 10	Widely implemented	Yes	Very short
Technical Design				
Light weight construction	< 7	Implemented	No	Very short
Optimum hull dimension	5 – 9	Implemented	No	Medium
Efficiency of scale	4 – 5	Implemented	No	Very short
Low profile hull opening	< 5	Narrowly implemented	No	Very short
Aft waterline extension	< 7	Narrowly implemented	Yes	Very short
Hull coating	0.5 – 5	Widely implemented	Yes	Very short
Covering hull opening	< 5	Implemented	Yes	Very short
Optimization water flow of hull opening	1 – 5	Implemented	Yes	Very short
Smaller engine	20 – 70	Implemented	No	Not known
Skeg shape/trailing edge	< 2	Implemented	No	Very short
Optimal propeller-	< 4	Narrowly	No	Very short

hull interaction		implemented		
Interceptor trim plates	< 4	Implemented	Yes	Very short
Ducktail waterline extension	3 – 7	Implemented	No	Very short
Air lubrication	3.5 – 15	Narrowly implemented	No	Short
Propeller-rudder combination	< 4	Implemented	Yes	Short
Propeller upgrade	0.5 – 3	Implemented	Yes	Medium
Propeller boss cap fins	1 – 3	Widely implemented	Yes	Very short
Optimization of propeller blade	2	Widely implemented	Yes	Very short
Counter-rotating propeller	10 – 15	Implemented	No	Medium
Wing thruster	< 10	Implemented	No	Short
Pulling thruster	< 10	Implemented	No	Short
Common rail	< 1	Implemented	Yes	Short
Diesel electric drive	< 20	Implemented	No	Short
Diesel-electric drive and diesel mechanical drive	< 4	Narrowly implemented	No	Medium
Main engine tuning	0.1 – 0.8	Implemented	Yes	Very short
Waste heat recovery (WHR)	< 10	Widely implemented	Yes	Short
Hybrid auxiliary power generation	< 30	Implemented	No	Very short
Low energy lightning and energy efficient appliances	0.1 – 0.8	Widely implemented	Yes	Short
Energy efficient HVAC	Not known	Implemented	Yes	Not known
Speed control of pumps and fans	0.2–1	Implemented	Yes	Medium
Scrubber	44 – 77	Narrowly implemented	Yes	Not known
Fuel efficient boilers	Not known	Implemented	Yes	Not known
Low loss power distribution	< 2	Implemented	No	Medium
Bulbous bow	≥ 10	Widely implemented	Yes	Very short
Shaft line arrangement	< 2	Narrowly implemented	No	Very short
Improvement of superstructure	2 – 5	Implemented	No	Short
Alternative lower carbon emission fuels				
Nuclear power	No CO_2 emission	Rarely implemented	No	Not known
LNG fuel	< 15	Narrowly implemented	Yes	Short
Bio fuels	< 78	Rarely implemented	Yes	Not known
Hydrogen	No CO_2 emission	Rarely implemented	No	Not known
Renewable energy				
Solar power	< 4	Narrowly implemented	Yes	Long
Towing kite	2.1 – 25	Narrowly implemented	Yes	Short
Wind engine	3.6 – 6.6	Narrowly implemented	Yes	Medium
Fuel cell	Not known	Rarely implemented	No	Not known
Wave energy	Not known	Narrowly implemented	Yes	Not known
Flettner-type rotors	< 30	Narrowly implemented	No	Medium
Using emission-capturing technologies				
Carbon capture and storage	10 – 20	Rarely implemented	No	Not known

• Technical information: Almost all LCS measures, especially by technical design approach are efficient or technical available with specific types of ship (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 & Utne, 2014) and decrease the performance of whole decision-making process. As the focus of the framework is on LCS measures decision making, these pieces of information require interaction between ship-owners and sources of information such as consultants, suppliers, service providers or research institutions in an individual base. Technical information set in this sub-stage may include:

a) Abatement potential: It is clear that LCS measures are purposed-built tools for decreasing CO2 emission and therefore the ecology aspect should be an essential criterion to evaluate them. This aspect expresses the ability of a specific measure in decreasing CO2 emission on a specific ship, in the form of CO_2 percentage decrease in case of 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. For the accuracy of assessment as well as performance in application, these statistics should be collected in a ship-particular manner with professional technical expertized supports. Table 1 provides an overview of different LCS measures. An introductive technical report from Buhaug et al. (2009) or updated information from Rehmatulla, Calleya, and Smith (2017) and Bouman, Lindstad, Rialland, and Strømman (2017) are available for this data entry.

b) Technology maturity: These pieces of information should be one of the inputs of prioritizing mechanism in the SADM stage. A trade-off could be observed here with the maturity of LCS technologies. By taking the risks of unstable, ineffective CO_2 reduction or higher operation and maintenance cost with the new technologies, the company could seek its advantages in other aspects such as better company image (pioneering and innovative in green technologies), possibly acceptable technical performance. In that sense, this factor explains the opportunity costs that the enterprise, invest in the measure later when it became matured and stable instead and have shorter payback time or greater benefit from it. However, 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 that considered as more matured will have lower risk level and higher certainty level concurrently.

c) Ability of technology support by government or industry bodies: If the decided technologies are promoted or encouraged by government or industry bodies, there will be advantages for company. Various supporting schemes for green technologies are available in the current trend of LCS. It could be supported financially by capital investment, incentive interest bank loan, or technology and know-how supports from most advanced technology institutions. The initiatives, funds, and collaborations established by IMO, Singapore, China, or UK are playing a vital role in LCS. Through these helpful mechanism, new LCS technologies becomes more attractive in the view of risk-takers in the industry. 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 critical information: Application process information; retrofit possibility; interference with other technologies or main operations; available area of application such as wind, solar, or speed reduction;

installation time; maintenance frequency; warranty policy and others. Contractors, suppliers, and service providers should be able to provide useful technical advises and prior examination/survey in collaboration with the company's own experts.

- 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, contractors, or service providers and intangible cost such as opportunity cost, restructuring logistic or supply chain cost, etc. These will be the input of the cost-efficiency analysis in the next stage, which indicate economic benefit from application of LCS measures. A comprehensive introduction on financial estimation of initial and maintenance cost could be found in the study of Buhaug et al. (2009) while Wärtsilä (2009) provided a catalogue with retrofit ability and payback time valuation.

- Total reduction potential of LCS measures combinations: In the study of IMarEST (2010), there are two reasons that LCS measures should be considered to exclude each other: (1) The overlapping effects of measures i.e. lowering CO2 emission in the same manner lead to reduce of overall result. (2) Practical reason i.e. 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.

A brief description of the data collection result could be as the example in Table 2.

Table 2

Example of data collection phase summary

Financial status	The amount of capital could be invested in the LCS projects: $3,000,000 USD with ± 5% tolerance
Ship status	Bulk carrier, 1 main engine, 2 auxiliary engines with available fuel consumption rate information 6-year-old with stable operational status, 1 major maintenance Reports, comments as well as supports of the former builder, served on-board officers, contractors, and consultants are available
Current competitive status and related strategies of the company	A medium-sized shipping company considers LCS as a profitable investing field. Blue shipping will be in the marketing strategy, depicts company's prospective vision and commitment to the market by going above the line drawn by law and regulation. However, service quality and reliability are still the highest priority
Fleet ecological status	Stable EEOI with an average value of 10 last voyage of 8.42864E-06. The main motivation of applying LCS is better energy efficiency and energy saving. This indicator as well as energy consumption rate will be used for assessment of LCS result post-installation.
Law and Regulation	The company still satisfies related all law and regulation layers with no immediate pressure
Industry practices	Experience and related information are available, but only in an introductory level
Relationship and coordination with other stakeholders	A good and wide relationship with ports and customers is maintained by the company. This make operational LCS measures that requires coordination among parties seem possible for future collaboration
LCS measures information	Only retrofittable measures will be considered. Due to limitation of operational schedule and technical ability, major or intrusive modifications of the main engine or crucial structure are not possible. Applicability and Capability checking is completed. Several possible alternatives could be considered with set of factors as Table 1, includes: Weather routing, Autopilot adjustment system, Integrated Propeller and Rudder upgrade, Hull coating, Towing kites, Propeller upgrade, or Low energy lightning and energy efficient appliances All data, including data of other aspects such as initial installation cost, maintenance requirements, life cycle, potential reputation impact will be provided by direct service providers and consultants for accuracy. Data sources as mentioned in Chapter 4 could be used for reference

5. Summarizing, Analyzing and Decision Making (SADM) process and derivation of outputs

5.1. *Applicability and capability*

This is the first step in the SADM block. The purpose is to qualify and narrow down the field of LCS options to prevent information overloading barrier (Table 3). Here happen the interactions between separated collections of input-stage. In specific:

Table 3

The information barriers encountered in improving shipping energy efficiency

Information barriers – Dimensions level	
-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: Adapt from Jafarzadeh and Utne (2014)

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

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

- *LCS technical information with coordination ability of stakeholders:* To reject inapplicable LCS measures due to 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 influence reach of enterprise, it should be rejected and held back for being as proposal in group scale.

- *LCS measures with an insufficient amount of collected data:* The measures which do not have enough information available 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 decision-making process.

5.2. *Cost and efficiency analysis*

The position of this part in the framework is clear – analyzing and assessing the financial impacts of LCS measures application on the enterprise, based on that to continue narrow down the field of available options and possibly become a criterion of the prioritizing mechanism. There are three primary results from this sub-stage:

- *Investment appraisal:* From data collected, 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. Advantages of NPV are the comprehensiveness of using information of capital, operational expenditures, fuel saving ability, investment lifetime to calculate the value of measures under the effect of discount rates. It ensures the simplicity but compactness of methodology:

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

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

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

$$R_t = FS_t - Cap_t - Opr_t - Opp_t \quad (2)$$

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 application of technology

Fuel saving (FS) can be calculated as:

$$FS_t = FSr \times OFC \times FP_t \quad (3)$$

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 enterprise, it should be rejected to avoid unnecessary further computation and consideration.

- *Reject LCS measures that have negative NPV (optional):* As seen in Table 1, majority of LCS measures have positive payback time, 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 the possibility that pressures from legal system is heavy enough to force enterprise to apply LCS technologies albeit their negative effects on the enterprise financial status.

5.3. *Prioritizing LCS measures using appropriate mechanism*

Obviously, this part of the framework is crucial since it is causally related to the ultimate decisions of stakeholders. Its general structure can be described as follow in Figure 2:

Fig. 2. Generic structure of the prioritizing mechanism

Depends on the requirements of the enterprise about LCS measures (which should be included in the internal and external situation realized in the Input block (Chapter 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. Requirements for algorithm using for prioritizing: (1) Able to handle input data but avoid loss of information analyzed from previous steps; (2) Able to assess alternatives in a multi-criteria basis; (3) Able to capture vagueness and lack of information. Moreover, simplicity and speed in application 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 & Peterson, 2014; Kesicki & Ekins, 2012; Kesicki & Strachan, 2011). As its mission, the prioritizing mechanism is employed to resolve two derived problems: (1) Finding the weight of criteria by which the LCS measures are evaluated; (2) Prioritization of LCS measures based on weighted criteria.

Either considering technological or operational measures, application of an LCS apparently has impacts on the company in multiple aspects. In fact, the relationship between 'environment' and 'enterprise', both positive and negative has been argued since a long time ago (Claver, Lopez, Molina, & Tari, 2007; Schaltegger & Synnestvedt, 2002). It is observable that environmental performance of a company is primarily based on the 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 progressively 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, Molina-Azorin, & Claver-Cortes, 2009). Claver et al. (2007) also indicated that an environmental strategy will definitely affect the firm performance, which is later defined as the combination of environmental performance, competitive advantage, and economic performance. Lastly, the uncertainty connected with new technologies application in general and of LCS measures in particular have to be assessed carefully beside mentioned factors. Therefore, we recommend four aspects as 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 should be presented by percentage of the potential CO_2 reduction rate which is achievable by using the measure.

- *Reputation and competitive advantage aspect:* The impact of each specific LCS measure to the image of the enterprise. Implementing new environmentally friendly technologies will probably differentiate the enterprise and improve its social performance. 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). 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 in assessment.

- *Economic aspect:* Lower CO_2 emission does not necessarily mean better energy efficiency. Even though this relationship is not yet well-known, the core performance of a company is undeniably economic performance and application of innovative technologies definitely has effects on the company's monetary flow. Consider this as an investment with its initial, maintenance, repair costs and returns are fuel savings. There are several possible measures for investment assessment appraisal discussed in Section 4.2.2.

- *Certainty aspect:* The consideration of applying modern technology always followed by the shortage of technical knowhow, technical support and risks in operation and maintenance. The certainty level in applying new technology also plays a critical role in decision making. There is always a gap between theoretical and practical performance of technology applications. Therefore, the certainty level of a potential LCS measure has to be considered concurrently. Study by Stevens et al. (2015) indicated that the excessively low certainty is a barrier to implementation of new green technologies. Uncertainty in adopting LCS measures can be found in several sections such as abatement potential, bunker price, effects on ship operations and maintenance. This aspect should be rigorously analyzed by the LCS measures assessment process which requires supports and judgements from experienced experts.

5.4. *Prospective MCDM methodologies*

It is mentioned that the proposed criteria are not always quantifiable from objective sources. While the ecological and financial aspects could be represented by the abatement rates as overviewed in Table 1 and financial appraisals as explained in Section 5.2, the impacts on the company's reputation or the certainty of the of individual LCS applications are still difficult to be directly measured. The prioritization mechanism, therefore, must be designed to handle different form of data input, both in exact number and linguistic assessments. A recommended mechanism for prioritization is presented in Figure 3.

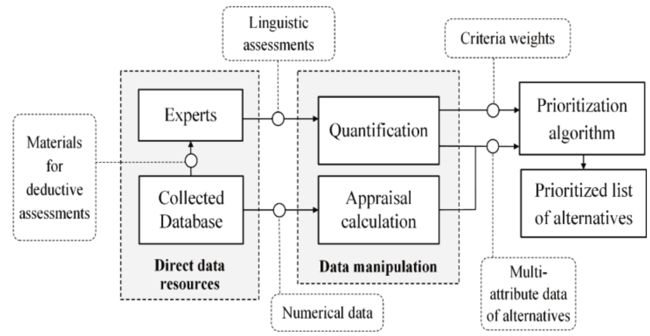

Fig. 3. Recommended structure of the prioritizing mechanism

At the moment there are several potential tools that allow us to accomplish these tasks while satisfy requirements declared in Section 5.3. Fuzzy theory by Zadeh (1965) is a widely recognized tool for handling vague variables as such. An advantage here is that many MCDM methodologies are available with their fuzzy-integrated variances such as Fuzzy Analytic Hierarchy Process (FAHP), or Fuzzy Analytic Network Process (FANP). Although being widely criticized, AHP is simple and quick to perform when the pool of alternatives is small (Wang & Nguyen, 2016). It is therefore feasible to use it for the purpose of criteria weighting. Fuzzy-based Technique for Order Preference by Similarity to Ideal Solution (FTOPSIS) could also be considered as a potential candidate here. The main idea of TOPSIS is to measure the distance from all the alternatives to the imaginary ideal ones (positive and negative) in a multi-dimensional space of different prioritizing criteria (Hwang & Yoon, 1981). The Outranking methods such as ELECTRE proposed by Roy (1991) or PROMETHEE of Brans, Vincke, and Mareschal (1986) are also designed to handle data shortage with qualitative assessments. A characteristic of outranking methods is the limitation of compensatory effects among multi-aspect performance of individual alternatives (Vasto-Terrientes, Valls, Zielniewicz, & Borràs, 2015). It is, therefore, have a better potential in dealing with "unbalance" alternatives where critical values present. There are many applications of MCDM techniques in the field of sustainable technology selection such as the study of Wang and Nguyen (2016) with the Fuzzy Quality Function Deployment (FQFD) and FTOPSIS as the prioritization apparatuses or Schinas and Stefanakos (2014) with AHP and ANP.

5.5. *Output – Important derivative results and LCS measures selection*

Based on the prioritized list of LCS measures, accessibility to capital, strategy of enterprise and other relevant factors, decisions of applying measures to limit the CO_2 emission can be made. Furthermore, decision maker can build up detailed plan for SEEMP implementation for both new and in-operation vessels (technologies or measure to be applied, their priority in 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 and ship operation and management activities (EEDI). While the former is the primary target of planning stage in SEEMP or the designing phase of a ship (EEDI), the later includes information for Implementation, Monitoring, Self-evaluation and improvement stages such as training process, application process, evaluation result of application and monitoring.

6. Discussion on the application of the framework

This paper proposed a planning support framework for shipping company in the way to approach higher energy efficiency and appropriate decision-making process in SEEMP, vessel design process, or LCS measures application in general. This data-oriented framework attempted to provide a manner to collect, summarize and analyze data, not only for the decision-making process itself but also could be used throughout SEEMP implementation process. Database collected was handled based on their interactions controlled by the decision maker. The framework structure was also built considering the information barriers to ensure prioritization performance but still avoid unnecessary pressure and workload on decision-making process. Applying this framework effectively is a rational manner to reduce CO_2 emission as well as increase energy efficiency of the fleet. The introduced framework attempted to make a bridge from the promulgation of SEEMP or EEDI and their actual implementation performance.

The offered framework has vital points that its users should notice in application. Firstly, the efficiency of the decision-making process depended heavily on the quality and sufficiency of the built database. Even if tools used in SADM block are advanced and efficient, the shortage or inaccuracy of database would fundamentally affect the usability of the results. On the other hand, the ability of the mentioned prioritizing mechanism was determined by the mathematical decision-making techniques used in action. The characteristics of the implemented methodologies should be considered rigorously in accordance with the form of the input data.

7. Conclusions

This study proposed a generic MCDM framework that positioned in the planning step of SEEMP. The way in which data is gathered, summarized, and analyzed while avoiding information losses and other barriers in the EEG is also brought to light. It was built in attempt to create a rational basis to support the implementation of SEEMP and further, a comprehensive tool for enterprises to apply in LCS measure decision making process. A categorizing scheme for data collection has been introduced together with screening processes and recommendations for a prioritizing mechanism. Finally, the framework was constructed in an open manner, which included components to be modified to fit in various situations of companies and vessels, increased its flexibility. Although the main target of the framework is possible to achieve, there are still limitations of this study. First, the application of the proposed framework in actual situations is still limited. Only a case study has been introduced in the study of Wang and Nguyen (2016), further application and performance benchmarking of it should be carried out. Second, as this is a generic framework, the operation manner and specific methodologies of prioritizing mechanism or decision-making sequential stages remain unspecified. For future study, we can clarify these processes by methodology recommendation and supplementing of lacking algorithm as well as validation process to enable their application in actual conditions.

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