Investigation on Marine LNG Propulsion Systems for LNG Carriers through an Enhanced Hybrid Decision Making Model

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Abstract

Since the use of LNG as an alternative fuel has drawn increasing attention from the marine industry, this paper aimed to evaluate three competitive LNG fuelled engine systems: ultra-steam turbine, four-stroke medium speed engine, and two-stroke low-speed engine systems. To achieve this goal, the paper developed an enhanced hybrid decision-making model which was applied to integrate the economic, environmental and technical performance of these systems. This model can be represented as a semi-quantitative multi-criteria decision making process in combination of several novel techniques, particularly *'life cycle cost assessment'* for economic analysis, *'life cycle assessments'* for environmental analysis, *'fuzzy order preference by similarity to ideal solution'* for technical analysis and *'fuzzy analytic hierarchy process'* for multi-criteria decision making. A case study with a 174K LNG carrier has revealed that the two-stroke low-speed engine system is the most effective overall and suggested that this type of engine system will hold the lead over the other candidates in the large LNG carrier market. It has also demonstrated the effectiveness of the proposed model to improve the inherent subjectivity in existing qualitative multi-criteria decision-making processes by guiding the overall process in a more objective direction. Finally, this paper has revealed an underlying novelty of the proposed model to enhance the level of confidence level in the decision by expanding our short-term perspective to the holistic one.

Keywords: life cycle assessment, multi-criteria decision making, marine LNG system, Fuzzy AHP, Fuzzy TOPSIS

1. Introduction

1.1. Background of gas-fuelled engines on LNG carriers

With an increasing environmental concern in the marine industry, International Maritime Organization (IMO) and local authorities have rectified a series of stringent regulations to curb the emissions produced from shipping activities. Above all, MARPOL Annex VI Regs 13 and 14 require progressive reduction of the emissions of nitrogen oxide (NO_x), sulphur oxides (SO_x) and particulate matters (PM) based on phased plans (IMO 2019a; 2019b).

Along with the technical advancement of LNG process systems, the use of LNG as a marine fuel source has been recognised as one of the most promising choices to meet those regulations. As a result, the number of LNG-fuelled vessels has steadily increased over the last decade, and by 2025, the global market for these ships will reach 700 in the world (DNV 2014).

This trend can be more clearly observed in the current market of LNG carriers where several types of marine LNG engine systems have been actively adopted: notably, the ultra steam turbines (UST), four-stroke medium speed engines (FME) and two-stroke low-speed engines (TLE) (MAN Diesel 2015).

On the other hand, this trend, leading to the diversity and complexity of maritime systems, has added the burden on shipyards and owners who always have to make the best choices to survive in fierce competition. In this context, a comparative analysis of these representative LNG engine systems in terms of economic, environmental and technical aspects can provide stakeholders with valuable insights into proper decisions.

1.2. Technical overview of LNG engine systems

The conventional propulsion system employed in most LNG carriers was an external combustion type that could run on both the boil-off gas (BOG) - a form of LNG vapour -, and liquid oil products. However, since 2000, the technical development of internal LNG combustion systems has diversified the choice of marine LNG engine systems. The representative systems in a tough competition are summarized as follows:

UST

UST is an upgraded system of conventional steam turbine (CST) system which can obtain propulsion power from main boilers. It uses intermediate pressure (IP) turbines to improve the efficiency by enriching heat capacity through the increase in the overheating level and the initial steam pressure.

FME

FMEs can run on both gas and diesel fuels; while the Diesel cycle is applied for the liquid fuel mode, the Otto cycle is adopted in the gas mode similar to the combustion method of an automotive gasoline engines.

TLE

TLEs differ from the FMEs in that the mechanism of engine combustion follows the Diesel cycle in both the gas and liquid fuel modes. In order to inject the fuel gas directly into the high-pressure combustion chambers, the fuel gas generally has a pressure as high as 300 bars.

1.3. Market overview and current issues

Fig. 1 shows the market trend of LNG engine systems for the LNG carriers over the six decades, revealing the four significant milestones.

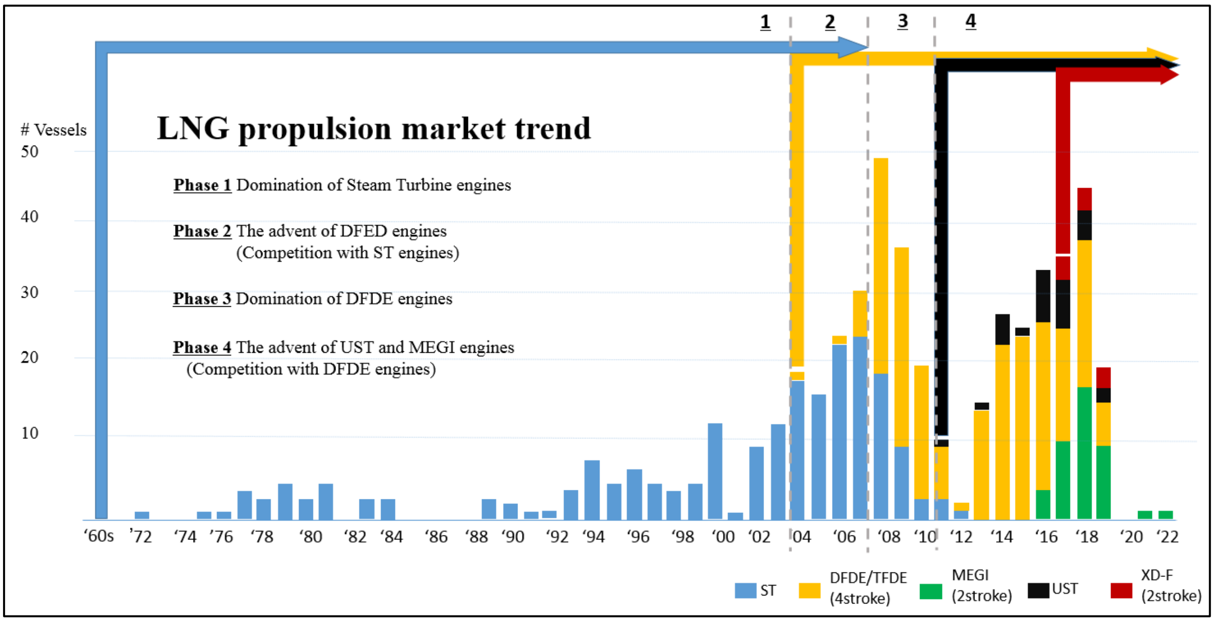


Fig. 1. LNG propulsion market trend (Tu 2019).

Phase 1 - 1960s to early 2000s: Era of steam turbine engines

Over the past decades, CSTs dominated the LNG carrier market as these systems were easier to manage the BOG and less costly than other candidates. The advantage of the steam turbine was that the pressure in the LNG cargo tanks could be controlled by burning the excess BOG naturally generated from LNG cargo.

Phase 2 - early 2000s to mid 2000s: Advent of FME and competition with steam turbine engines.

The technological advancement of the onboard BOG handling systems (known as the re-liquefaction system) has brought out a new era in LNG carrier market. Since the early 2000s, FMEs began to be adopted as a propulsion system for LNG carriers. For that reason, the intense competition between CSTs and FMEs has continued until the mid 2000s.

Phase 3 - mid 2000s to early 2010s: Domination of FSEs

During this period, the FMEs were proved to improve operational flexibility and fuel saving by up to 40 % compared to CSTs, which forced CSTs to withdraw from the market (Wartsila 2016; Kwon 2017). Eventually, the FMEs have taken the leading position in the market.

Phase 4 - early 2010s to present: fierce competition across two, four-stroke gas engines and ultra stream turbine.

Since the beginning of 2010, the marine engine market has encountered a new challenge with the introduction of USTs as well as TLEs. The market share of the FMEs is still high, but the strengths of the two counterparts have begun to be acknowledged and gradually penetrating the market.

During ship building, innumerable decisions are to be made. Given that the propulsion system is one of the most important parts of ship, a proper decision making in engine selection is exceptionally valuable.

The tremendous amount of CST and FME operating records contrasts with the brevity of TLEs and USTs, which may interferes with proper engine selection.

The engine manufacturers tend to highlight the advantages of their products while to avoid disadvantages in terms of sales. To ensure the optimal choice objectively, the extensive data needs to be collected, analysed and compared from diverse stakeholders: not only manufacturers, but also industrial advisors and exerts who have experience of operation and maintenance of the propulsion systems and crew members. Due to lack of trained staff and relevant tools, ship-owners are least motivated to carry out logical process of decision making. Consequently, as a culture of ship building process, they tend to decide what they are most familiar with. Evidently, there lacks research on systematically comparing the three representative nominees.

On the other hand, such a muddled practice don't provide much evidence of logic, good input, fairness, or representation of interests. Therefore, the easier it is for ship-owners to walk out of the room with the wrong message with a plenty of room for errors and misunderstandings (Jeong et al. 2018b).

Nonetheless, propulsion systems have a significant impact on cost, emissions and safety, so the marine industry should promote the use of logical decision-making processes that will contribute to business success.

1.4. Research aim and direction

This research was motivated to answer the fundamental question on identifying the engine system that ultimately outperforms the others in the large LNG carrier market. Therefore, this paper sought to provide a holistic view of the strengths and limitations of the three engine systems by analytically exploring their performance from the economic, environmental and technical perspectives with various methods. In particular, life cycle cost assessment (LCCA), life cycle assessment (LCA), fuzzy analysis, multi-criteria decision making analysis (MCDM) were combined together to draw the final outcomes. Therefore, the proposed model can be expressed as a hybrid decision-making model. Such a combination of noble technologies not only improves the reliability of the MCDM, but also extends the scope of analysis systematically taking into account various aspects. To prove the suitability of the proposed model, a case study with a 174,000 m^3 LNG carrier was proposed to evaluate the best engine system from a comprehensive viewpoint.

2. Method applied

2.1. Overview of life cycle assessment (LCA)

LCA was born with the great concerns on environment during 1960s. In 1969, the US Coca-Cola analysed the comparative study of beverage containers as an effort to minimize environmental pollution and natural resource depletion. This work was recognised as the first LCA (Guinee et al., 2010).

Facing the global oil crisis in the early 1970s, research on energy demand and supply for fossil fuels and renewable energies boosted the interest in LCA. However, as the oil shortage stabilised, such an interest in LCA research began to decline. Once again since late 1980s, LCA was resumed due to global waste issues and became a tool for solving environmental problems (LeVan, 1995).

In the 1990s, the Environmental Toxicology and Chemistry Association (SETAC) actively participated in the LCA field. This indicates that LCA practitioners, users and scientists have begun to establish basic concepts, understandings and approaches to LCAs (Guinee et al., 2010).

Lastly, the process of LCA was standardized by the International Organization for Standardization (ISO) and after being revised, these standards which are ISO 14040 and ISO 14044 have been extensively used in a variety of fields such as automotive, construction, etc (ISO, 2006).

LCA was first introduced to the shipping industry in the 1990s by Annik Magerholm Fet (1996) who attempted to estimate the environmental impacts of platform supply vessels. The following research was made with M/V Color Festival, a roll-on / roll-off vessel in 1999 (Johnsen and Fet. 1999).

Since the mid-2000s, LCA-based ship design, ship building and operation have started to gain more and more attention. This resulted in the development of a software tool known as LCA-ship (Jivén et al., 2004).

There are some notable LCA studies related to the marine engineering to be introduced. Alkaner and Zhou examined the performance of alternative power sources by comparing dissolved carbon fuel cells with marine diesel engines (Alkaner and Zhou, 2006). This comparison was implemented in practice (Bengtsson, Andersson, and Fridell, 2011).

Kameyama, Hiraoka, & Tauchi, (2007) conducted an assessment of ballast water treatment systems (BWTS) that emphasized social sustainability assessment. Similar works with BWTS were introduced by several research publications: Blanco-Davis and Zhou (2014) and Basurko and Mesbahi, (2014).

Notable LCA work has been carried out through the EU project Eco-REFITEC, which aimed to provide technical support to EU repair shipyards (Blanco-Davis, 2015, Blanco-Davis, Del Castillo, & Zhou, 2014, Blanco-Davis & Zhou. 2014).

2.2. Overview of multi-criteria decision making

Compared to single-criterion decision making analysis, MCDM can interpret the complexity of various characteristics of credible options. In general, MCDMs are applied to help decision-makers to map and systematize problems in order to make informed choices. Various techniques have been developed and implemented across industries. Wang et al. (2009) reviewed the published research on MCDM applied to sustainable energies, pointing out the increasing popularity of MCDM methods in the area. the MCDM applications can be found in some of the latest studies presented below:

> Stoycheva et al. (2018) introduced an MCDM framework to evaluate the sustainability of the automobile manufacturing industry. From the social, economic and environmental aspects, they mainly assessed the optimal selection of the raw materials among various options.
>
> Neves et al. (2018) also adopted a conventional MCDM to evaluate the sustainable energy strategy of Portugal.

On the other hand, despite the considerable efforts for evaluating the impacts of various aspects, the use of MCDM in these studies appeared still limited to qualitative approaches. In this context, the fuzzy theory is often incorporated into conventional MCDMs in efforts to enhance the reliability of the decision-making processes. Here are some key fuzzy based MCDMs worth being discussed;

> The fuzzy analytic hierarchy process (AHP) - a combined technique between the fuzzy theory and AHP method - was developed to remedy the drawbacks of the conventional AHP and to solve real-life problems reliably. Van Laarhoven and Pedrycz (1983) were known as one of the first fuzzy AHP applicators by defining the triangular membership functions for the pairwise comparisons. The research was succeeded by Buckley whoc (1985) contributed to the determination of the fuzzy priorities of comparison ratios with triangular membership functions. Since then there have been a number of research introduced with fuzzy AHP

methods.

Fuzzy order preference by similarity to ideal solution (fuzzy TOPSIS) is an enhanced process of TOPSIS which was initially developed by Hwang and Yoon (1981) (Tzeng and Huang 2011) and further elaborated by Yoon (1987) and Hwang et al. (1993). The basic idea of this technique is that the selected candidate has the shortest geometric distance from the positive ideal solution (PIS) and the longest geometric distance from the negative ideal solution (NIS). The fuzzy theory reinforces the application of TOPSIS to areas where data is often incomplete or inconclusive.

The fuzzy based MCDM processes have been extensively applied to research in a variety of industries. Obviously, voluminous studies using these techniques have been published. On the other hand, these techniques appears to be immature in the marine/offshore industry, considering the number of publications in the past. Despite the lack of applications, some outstanding maritime research is worthy of being presented as below:

Wan et al. (2015) investigated the excellence of LNG-fuelled ships through a hybrid MCDM analysis in which the SWOT (strengths, weaknesses, opportunities, and threats) analysis combined with the AHP. They invited 16 experts to assess various aspects of using LNG as a marine fuel. Likewise, scoring for each criterion was made by the expert knowledge.

Lazakis and Ölçer (2016) evaluated the best maintenance approach for shipboard equipment, using the technique of fuzzy-TOPSIS analysis. They linguistically assessed the advantages and disadvantages of three maintenance strategies - namely corrective, preventive and predictive maintenance - based on the four experts' judgements.

Balin et al. (2016) adopted a hybrid MCDM model, a combination of Fuzzy AHP and TOPSIS methods, to investigate various failures associated with gas turbine components.

This study concluded that the proposed hybrid MCDM was effective in evaluating the best equipment to minimise such failures.

Stavrou et al. (2017) have developed an MCDM model, based on the ELECTRE method and selected the optimal ship-to-ship bunkering location in accordance with the operational eligibility.

However, the past research could not be free from uncertainties originated from human subjectivity. Several studies have made interesting attempts to address this limitation.

2.3. *Combination of LCA with MCDM*

Some noteworthy studies focusing on environmental impact assessment include:

Myllyviita et al. (2012) assessed the environmental impact of biomass production chains with a combined method between LCA and MCDM. In this case, MCDM was applied as a normalisation tool. Domingues et al. (2015) assessed the environmental impact of various vehicle fuel types using LCA model. Then, it involved a conventional MCDM to determine the optimal fuel solution.

Sohn et al. (2017) carried out LCA which was coupled with a conventional MCDM for investigating the effective level of industrial building insulation.

Miah et al. (2017) reviewed recent publications dealing with enhanced MCDMs. The findings concluded that various fields had accommodated the hybrid frameworks which could improve the reliability of decision-making. A similar work was also done by Martín-Gamboa et al. (2017). Their work was focused on the methods to assess the sustainability of energy systems: notably, it discussed MCDM in the combination of LCA and data envelopment analysis. They pointed out the high capability of such a combination when assessing case studies. Zanghelini et al. (2018) reviewed the effectiveness of the combination MCDM and LCA on environmental impact assessment of various systems and processes. The focus of these reviews was on exploring how effectively the MCDM techniques can be coupled with the LCA context to aid the assessment of the environmental impacts of various systems and processes.

However, the use of MCDM technique for such research was largely limited to the of the environmental impact assessment as a single criterion. Given that a decision is made in consideration of various aspects rather than a single one, more comprehensive models are to be introduced in order to integrate the impacts of diverse criteria together.

2.4. Shortcomings of conventional MCDM approaches

Previous research may lead us to the agreement that the MCDM methods are robust for proper decision making in consideration of the complexity of options' characteristics, provided that the proceedings of criteria selection, weighting and assessments are appropriate for specific decision problems.

Although it does not deny the benefits in using qualitative MCDM methods, they have several inherent shortcomings (Vinnem 2007; Rausand and Høyland 2004; Jeong et al. 2018) as described below:

- It could be problematic when assessing the advantages/disadvantages of systems for which there is a lack of knowledge and experience.
- It is difficult to make a quantitative prediction with high credibility because the knowledge produced might not be generalised to other people or other cases.

- It overly relies on the experts' judgement and experience, possibly bringing personal biases into the process, thereby leading to misjudgement.
- It reveals the lack of the holistic view in decision-making.

It revealed that the initial data for assessment was driven from psychological or qualitative sources, like expert judgement. Therefore, it is thought that if an expert makes a wrong judgement, the conventional MCDM can mislead conclusions. Moreover, despite the remarkable technological advancement in the marine LNG propulsion systems, the systematic investigation into the advantages and disadvantages of different engine concepts are insufficient. In this context, the likelihood of professional misconduct may be higher than when performed with proven systems. In order to remedy such inaccuracies or vagueness inherent in the information provided by a human, an enhanced approach was proposed in this paper.

Moreover, the previous maritime research somewhat lacked a holistic view of decision making. Although a ship has several life stages from the cradle to the grave: mainly, construction, operation, maintenance and scrapping (Jeong et al. 2018), the practice of the existing MCDMs is due largely focused on specific parts of the ship's life, providing only a narrow view in decision. For example, in the interest of shipbuilders, analytic research is more likely to be applied for the shipbuilding stage, but from the ship-owners' perspective, it may be concentrated on the operation and maintenance stages. Such restricted analyses may prevent us from making trustworthy decisions.

2.5. The enhanced method with the proposed idea

The underlying idea placed on the proposed model is that numerical or quantitative values would help people make the right decision with higher confidence. The overall process of the projected MCDM is outlined in Fig. 2 which is an enhanced version of the conventional MCDM in consideration of economic, environmental and technical aspects.

In this principle, the economic and environmental impacts of target options can be quantified through the LCCA and LCA, and the technical impact can be assessed on the basis of the fuzzy TOPSIS. Thereafter, the impact of each criterion on a subject option is integrated and compared to those obtained from alternative options by using the fuzzy AHP. This integration process is believed to make the analysis more extensive and reliable, reducing the human subjectivity. Therefore, the proposed approach was applied to a case ship to which the credible three engine systems were imaginary fitted.

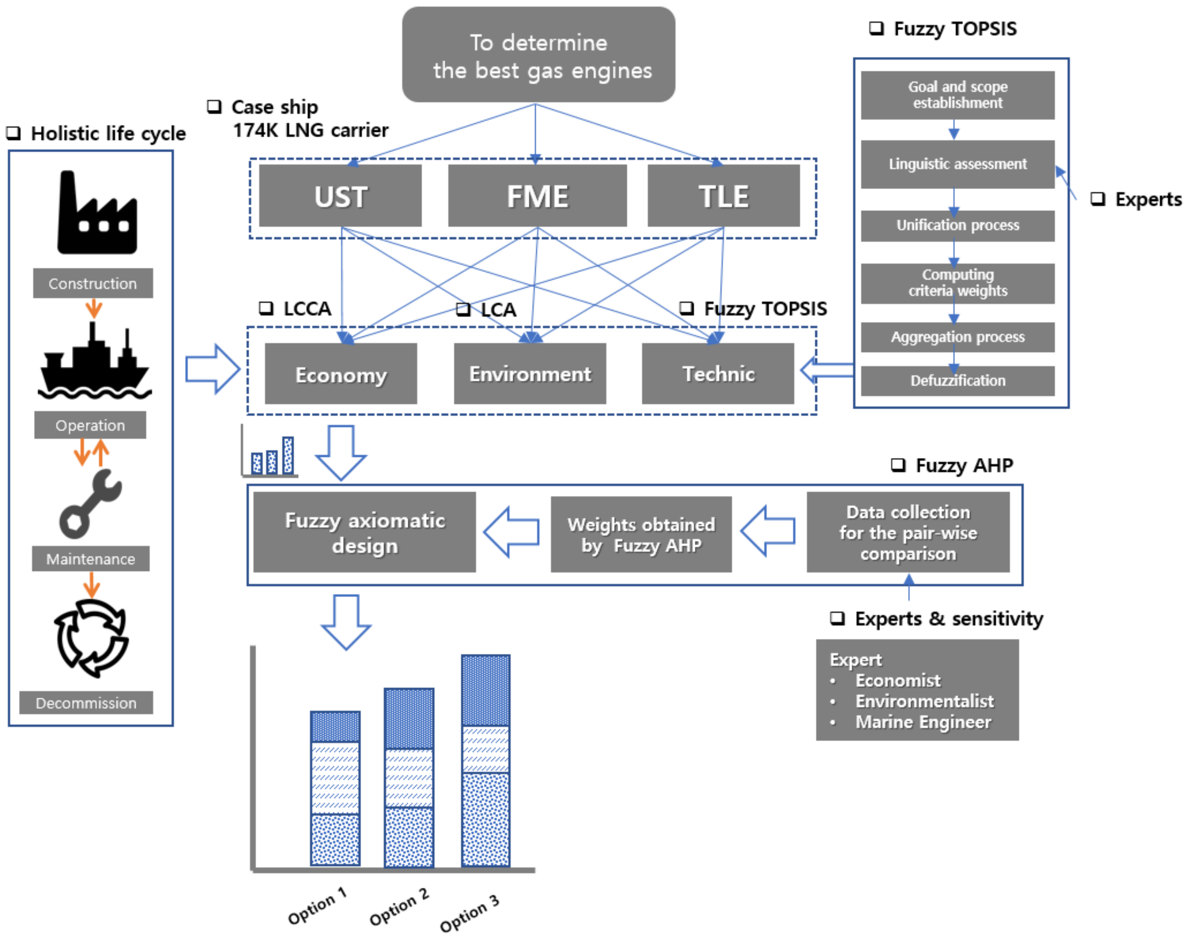


Fig. 2. Outline of the proposed MCDM for maritime gas engines.

2.5.1. Economic impact

The economic impact can be expressed as a combination of the total costs relating to the outcome of selecting options over the ship's lifetime. This impact has a negative influence on the decision-making, so lower values are a better choice. Taking into account the ship life stage, this paper estimates the entire costs by integrating the expenses in four categories: construction, operation, maintenance and decommission.

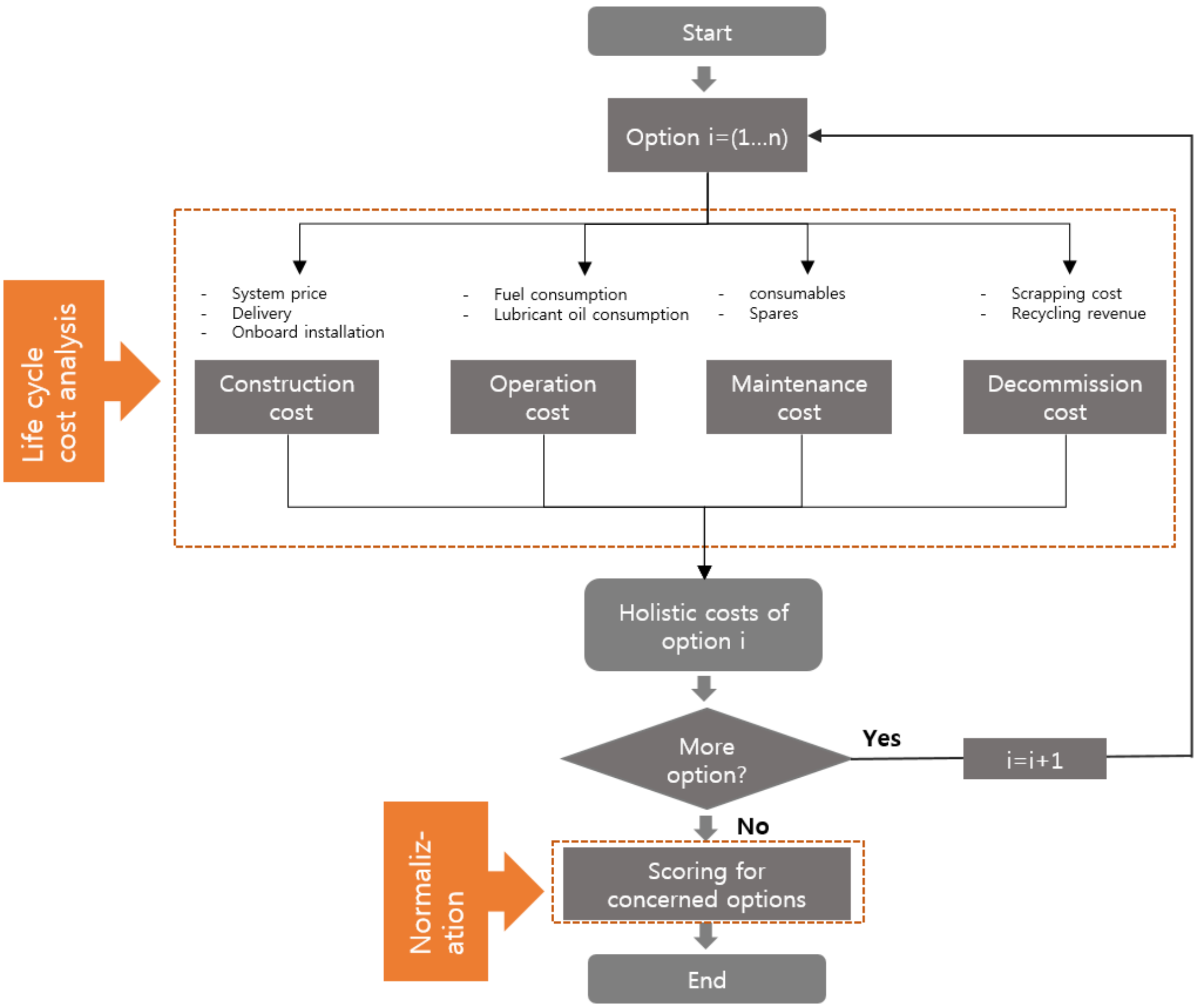


Fig. 3. Outline of the proposed approach on investigating the economic impact.

<u>Construction cost</u>

The construction cost, which can be described as the initial cost, represent the sum of the expenses of products and services such as delivery, onboard installations, engineering works, etc.

Operational cost

The operational cost pertinent to ship service is mainly contributed by the fuel costs directly related to engine fuel consumption that can be calculated based on Eq. (1) (Jeong et al. 2018). The SFOC related to energy consumption was determined by courtesy of the engine manufacturers.

$$OC = \sum_{i=0}^{n} \left(SFOC_i \times RP_i \times t_i \right) \times FP \tag{1}$$

Where,

RP_i	Required power at operational condition, i (kWh)
OC	Operation cost
$SFOC_i$	Specific oil/gas consumption at operational condition, i
t_i	Time spent at operational condition, i
FP	Fuel price ($)
Index, i	particular operational condition (three representative conditions were assigned for this study: berthing, maneuvering and transit)

Maintenance cost

Engine systems are subject to regular maintenance from daily inspections to overhauls. The maintenance plan is generally scheduled according to the engine running hours. The maintenance costs are related to the costs of supplies, consumables and spare parts that need to be updated on a regular basis. Given that on-board engineers usually are responsible for maintenance work, labour costs (already included in their wages) were not necessarily considered in this paper.

Decommission cost

At the end of ship life, recycling or disposal of engines is also included in financial consideration, so that equal importance needs to be paid to the decommissioning cost or revenue for engines. Table 1 shows the material content and recycling revenue from a typical marine engine.

Table 1

Material content and recycling price of a typical marine engine (Scania 2016; ScrapSales 2017).

Engine Material	**Recycling metal price** (USD / kg)
Steel	$0.190
Cast iron	$0.110
Aluminium [Al]	$1.990
Copper [Cu] and Zinc [Zn]	$4.770
Lead [Pb]	$1.330
Plastic	-
Rubber	-
Paints	-
Oils and Grease	-

Financial parameters to be considered

- *Discount rate:* in order to consider the monetary value of time, the discount rate was generally assumed to be 5 %.
- *Service life:* it corresponds to a life expectancy of ship or engine systems. Most ships are built of welded steel, generally having a lifetime of 30 years. On the other hand, LNG carriers are intent to be considered more conservative even if their actual lifetime is longer. In the real project inspiring this research, moreover, the LNG carrier has agreed to engage in 20 year service between the United States and South Korea. Therefore, it is appropriate to assume that the life of the case ship is 20 years.
- *Fuel prices:* market prices of fuels include the expenses of fuel extraction, mining, transportation and processing for onboard usage, which may vary considerably depending on different time periods and geometrical regions. This research referred to the fuel prices in May 2018: USD 2.91/MMBtu for LNG and USD 695/ton for marine gas oil (MGO) (Ship&Bunker 2018).

The overall economic impact of the proposed systems can be expressed based on Eq. (2).

$$NPV_{final}=CC+DC+\sum_{t=1}^{n}\frac{1-(1+r)^{-t}}{r}\times(OC_t+MC_t) \quad (2)$$

Where,

NPV_{final} Final net present value

CC Construction cost

OC_t Operation cost at given year, t

MC_t Maintenance cost at given year, t

DC Decommission cost

r Discount rate (%)

2.5.2. *Environmental impact*

Error! Reference source not found. illustrates the process of estimating the holistic environmental impact of the feasible options. The environmental impacts for the marine engine systems were investigated based on the LCA approach which was primarily guided by the International Organisation for Standardization (ISO) (ISO 2006a and 2006b). The computational tool, GaBi software provided by PE International GmbH were used to support the analysis (PE 2018). The types and quantities of emissions associated with the processes involved in this analysis were quoted from the GaBi database, while the rigorous review of wide-ranging publications in both academy and industry was conducted to obtain supplementary data that Gabi database could not provide.

In the first phase, the research objectives and scope are clearly set. The life cycle inventory should then be analyzed taking into account the energy consumptions and emission productions from all relevant activities of the specific product from cradle to grave: maybe including material extraction, transportation, manufacture, use and disposal stages.

Potential environmental life cycle impact assessments are performed with input / output data derived from the life cycle inventory stage. The selection of the impact categories and evaluation methods for each category are subject to the purpose of the study: generally including resource depletion, ozone depletion, global warming, eutrophication, acidification, photochemical oxides and human toxicity. At the last stage, the interpreted LCA results are ultimately to represent the holistic environmental impact of the proposed model/system as internal process environmental conditions. It can, therefore, provide reasonable criteria or insights for eco-friendly design and production.

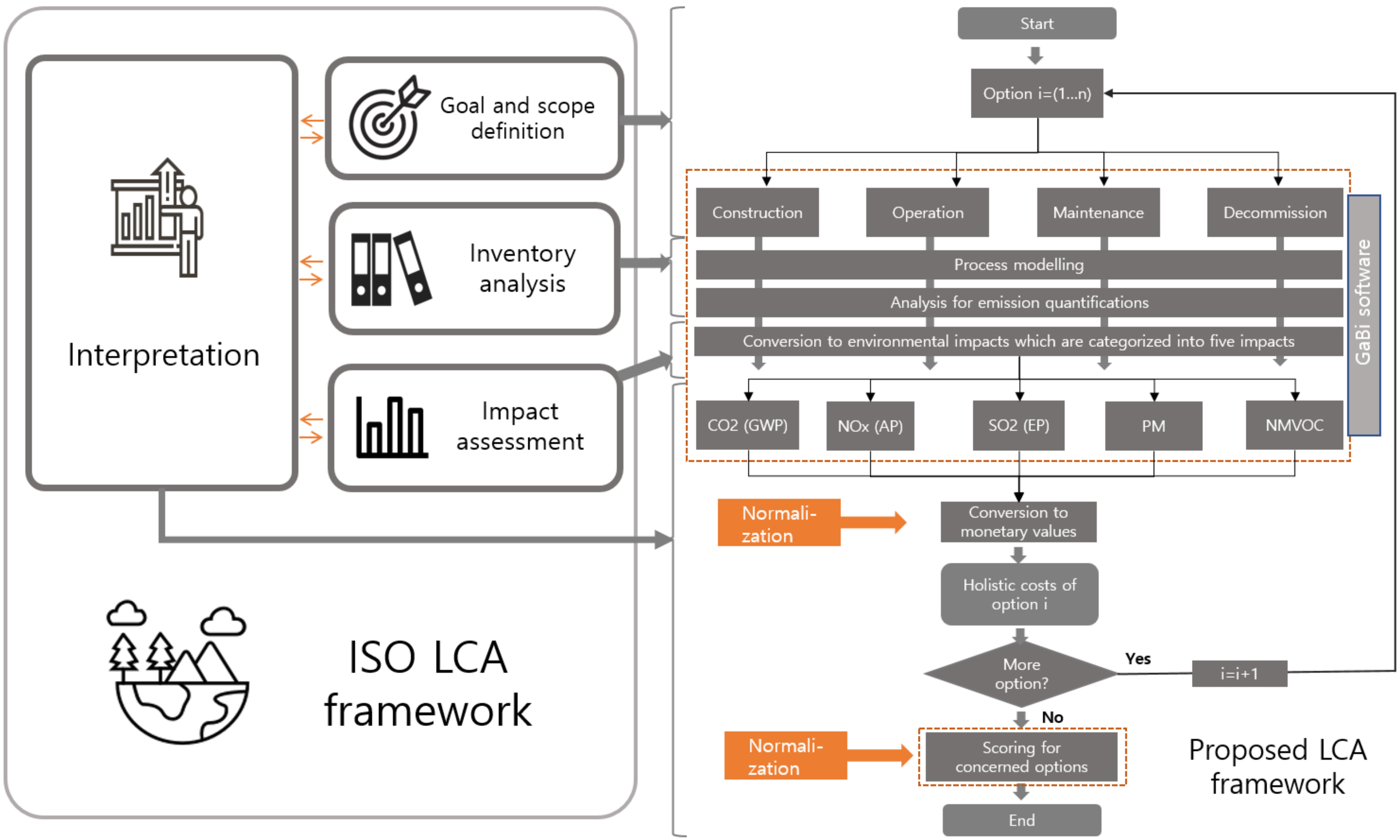


Fig. 4. Outline of the proposed approach on investigating the environmental impact.

Focusing on the case study for this paper, ship activities associated with the particular options have been modelled at different ship life stages. The purpose of such modelling was to track emissions produced throughout all activities such as the material production, transportation and energy consumption, thereby estimating the environmental impact of those options. The result of analysis generally indicates more than 100 emission types and this paper normalised and converged them into the five major marine pollutants using CML2001 (CML 2016) and ILCD PEF (JRC 2010), an environmental impact assessment method: nitrogen oxides (NO_x), non-methane volatile organic compound (NMVOC), sulphur oxide (SO_2), particular matter ($PM_{2.5}$) and carbon dioxide (CO_2).

- **NO_x**: it is a generic term for the nitrogen oxides, mainly nitric oxide (NO) and nitrogen dioxide (NO_2) which are primarily attributed to acid rain and ground level ozone as well as adverse health effects such as respiratory problems. NOx emissions from ship engine combustion processes are progressively restricted by IMO MARPOL Annex VI Reg. 13.
- **SO_2**: Sulphur dioxide is a highly toxic, colourless, non-flammable gas, which is generated from fossil fuel combustion. IMO MARPOL Annex VI Reg. 14 strictly limits the maximum sulphur content of the marine fuel oils in order to curb the SO_2 emissions from ship service.
- **NMVOC**: As a collection of organic compounds, NMVOC is emitted into the atmosphere from substantial combustion activities in the marine industry. This type of emission is hazardous to human health as well as contributing to the formation of ground level (tropospheric) ozone. The production of NMVOC during the ship service is rigorously controlled by IMO MARPOL Annex VI Reg. 15.
- **CO_2**: Not only the marine industry but also all other sectors, carbon dioxide is regarded the culprit contributing to global warming. IMO Resolution. MEPC.203 (62) provides a series of guidelines to measure, monitor, track and finally reduce this emission. Moreover,

IMO MEPC at its 72nd session adopted the IMO's Greenhouse Gases Emissions strategy as a framework for guiding principles and lists potential short, mid and long-term further measures to reduce GHG emissions with possible timelines (IMO 2018).

- **$PM_{2.5}$**: It is the term for a mixture of solid particles and liquid droplets found in the air such as some particles, such as dust, dirt, soot, or smoke, are large or dark enough to be seen with the naked eye. Fine particles (PM2.5) are the primary cause of reduced visibility (haze) as well as human health problems. Along with the limit of SO_x, IMO MARPOL Annex VI Reg. 14 strictly controls the production of PM during ship service.

As the interpretation work for comparison, all emissions were converted into monetary values designated by EU; the prices given to each emission type can be regarded a different format of weights on the different impact of emissions. The values were given through a thorough investigation of experts through several EU projects (Maibach et al. 2008). For instance, the monetary value of CO_2 is \$24/tonnage and that of NO_x is \$4,602/tonnage in the UK. From this information, we can objectively infer that one tonnage of NOx emission would have 191 times higher adverse impact on the environment than one tonnage of CO_2.

Construction phase

The energy consumed in the ship construction phase mainly accounts for the manufacturing and production for the following items: steel plates, supporters, engines, equipment, fittings, paints, etc. (Shama 2005). Regarding the scope of this paper, a focus was placed on the production and installation of the main engine systems as outlined in Fig. 5.

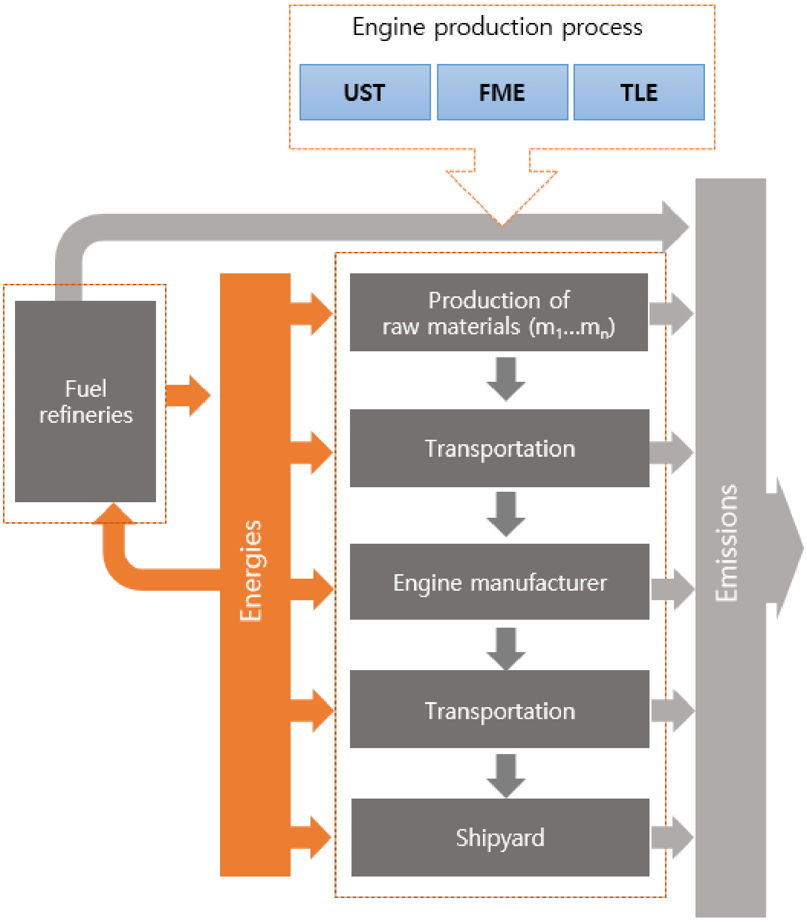


Fig. 5. A process of ship construction associated with engine systems.

The LCA for the engine systems begins with the proper process modelling from the manufacturing to the onboard installation. This model assumed that the raw materials would be produced in steel industries and transported to engine manufacturers whose raw materials would be processed into engine systems. The completed items are delivered to the shipyard and finally installed in the machinery space. The energy usage for each activity is analysed based on the electricity consumptions: 8.5 MJ/m for steel cutting, while 15.1 MJ /m for the welding (Gilbert et al., 2017).

Operation phase

It needs to be repeated that that the vessel operation phase is primarily concerned with the cargo transport to a specified distance and the main energy consumption is related to the operation of the engine system. Fig. 6 shows this scope of the process in the ship operation phase.

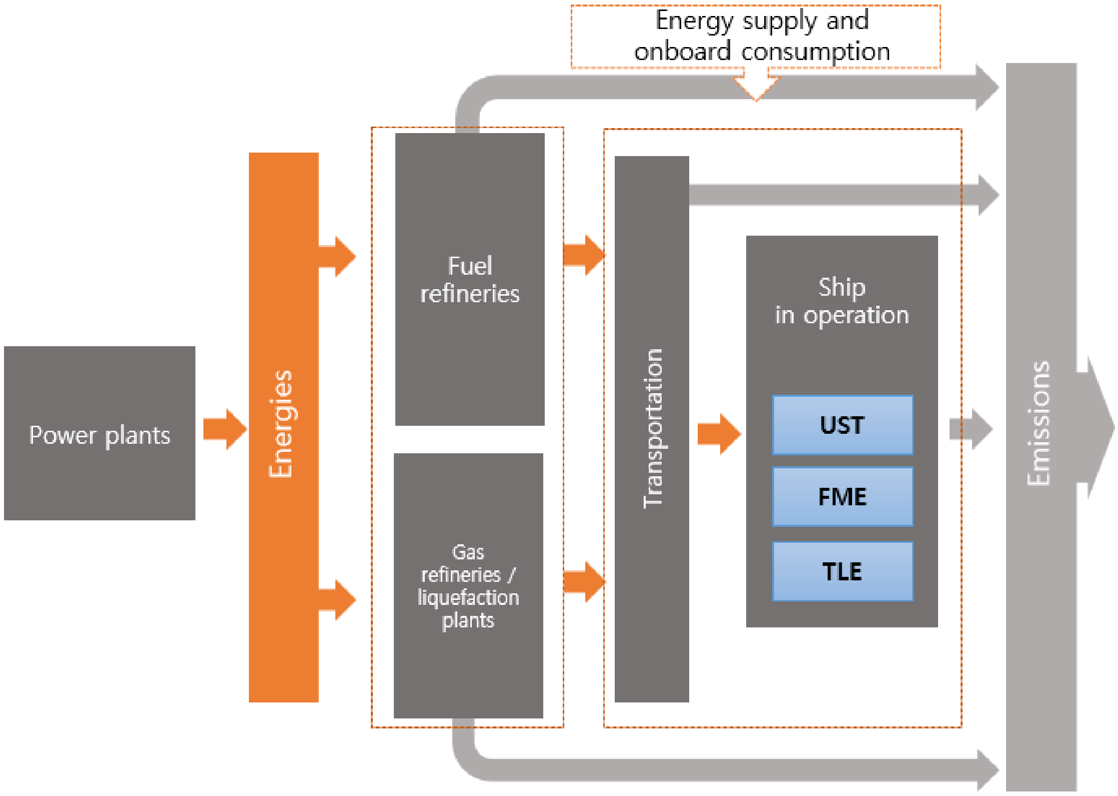


Fig. 6. A process of ship operation associated with engine systems.

Table 2

Average emission factors for top-down emissions from typical fuel combustion (IMO 2015).

Emissions substance	Marine HFO emissions factor (g/g fuel)	Marine MGO emissions factor (g/g fuel)	Marine LNG emissions factor (g/g fuel)
CO_2	3.114	3.206	2.75

CH_4	0.00006	0.00006	0.0512
N_2O	0.00016	0.00015	0.00011
NO_x	0.093	0.08725	0.00783
CO	0.00277	0.00277	0.00783
NMVOC	0.00308	0.00308	0.00301
SO_x	0.04908	0.00264	0.00002
$PM_{2.5}$	0.00699	0.00102	0.00018

Maintenance phase

In terms of environmental impacts on engine maintenance, the related activities were considered relatively immaterial because spare parts renewals and engine overhauls are scarcely sensitive to the significance of electrical consumption, compared to activities in the other phases (Jeong et al. 2018). In this context, this paper was convinced to disregard this phase.

Decommission phase

The ship was assumed to be delivered to a recycling facility where the mechanical systems are to be disassembled along with ship structures. The related activities were modelled to estimate energy sources and emissions as shown in Fig. 7.

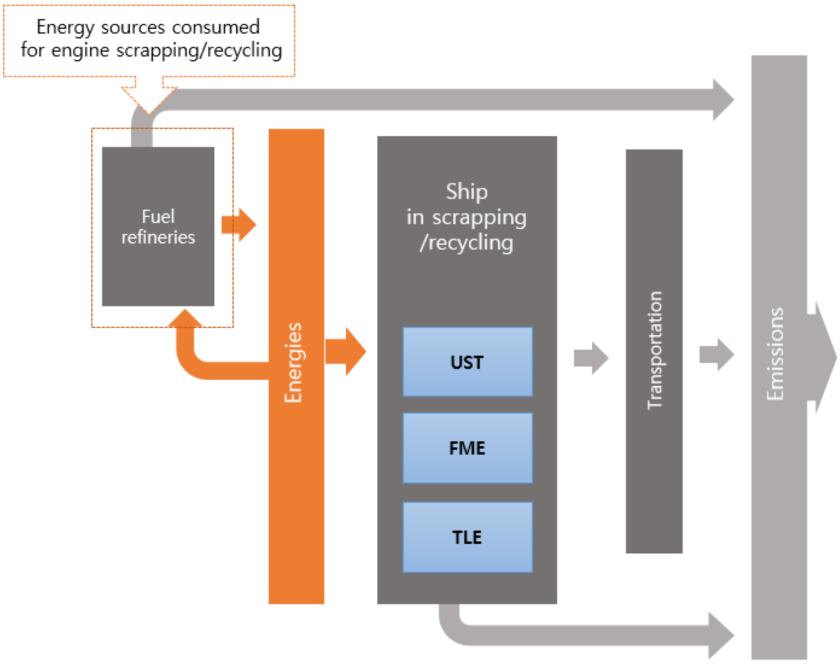


Fig. 7. A process of ship decommission associated with engine systems.

Presumably, the parts of the material constructing the engine systems are to be recycled whereas some other parts are to be scrapped. Thanks to the efforts of various researchers, the summary of the energy consumed and emissions produced for recycling process can be shown in Table 3 (Ling-Chin and Roskilly, 2016; Jeong et al. 2018).

Table 3

The summary of the energy consumed and emissions produced for recycling process (Ling-Chin and Roskilly, 2016; Jeong et al. 2018).

Item			Steel and cast iron	Stainless steel	Al	Cu	Zn	Pb	Ni
Key references			(Yellishetty et al., 2011; Norgate, 2014)	(Crundwell et al., 2011)	(Gaustad et al., 2012; Paraskevas et al., 2015)	(Muchova et al., 2011)	(Gordon et al., 2003)	(Genaidy et al., 2009)	(Johnson et al., 2008)
Energy	MJ	Electricity	1.71	7.18	0.10	-	0.73	-	1.92
		Natural gas	0.62	2.60	10.22	-	0.34	-	2.30
		Coal	-	-	-	-	1.46	-	1.71

		Blast furnace gas	-	-	-	4.95	-	7.00	-
		Heavy fuel	-	-	-	-	-	-	0.22
Material	kg	Pig iron	0.02	0.06	-	-	-	-	-
		Oxygen (l)	0.04	0.17	-	-	-	-	-
Emission	Kg	SO_2	1.02E-04	4.28E-04	4.41E-03	2.00E-05	3.67E-03	2.00E-05	-
		NO_x	2.40E-04	5.27E-06	2.65E-03	7.00E-05	1.57E-03	7.00E-05	-
		CO_2	1.05E-01	4.41E-01	5.45E-01	2.00E-01	-	2.00E-01	1.19E-02
		CO	2.40E-03	1.01E-02	8.83E-04	1.50E-05	-	1.50E-04	-
		$PM_{2.5}$	1.59E-02	6.71E-02	8.83E-04	1.90E-04	3.94E-05	7.90E-03	2.95E-04
		PM_{10}	2.01E-04	8.46E-04	-	2.60E-04	7.56E-06	1.06E-02	4.29E-05

Conversion to monetary values

The weighting process was applied to consolidate the various types and amount of emissions estimated in the analysis into a single comparable unit. The conversion factors (expressed here as monetary values) were added to each type of emissions in accordance with the emission database with potential emission costs priced across the European countries (Maibach et al. 2008): based on EU- 25, NO_x (USD 5,150/ton), NMVOC (USD 1,300/ton), SO_2 (USD 7,750/ton), $PM_{2.5}$ (USD 30,500/ton), CO_2 (USD 36/ton).

2.5.3. *Technical impact*

Fig. 8 shows the Fuzzy-TOPSIS analysis process expected to complement the disadvantages of the existing TOPSIS analysis.

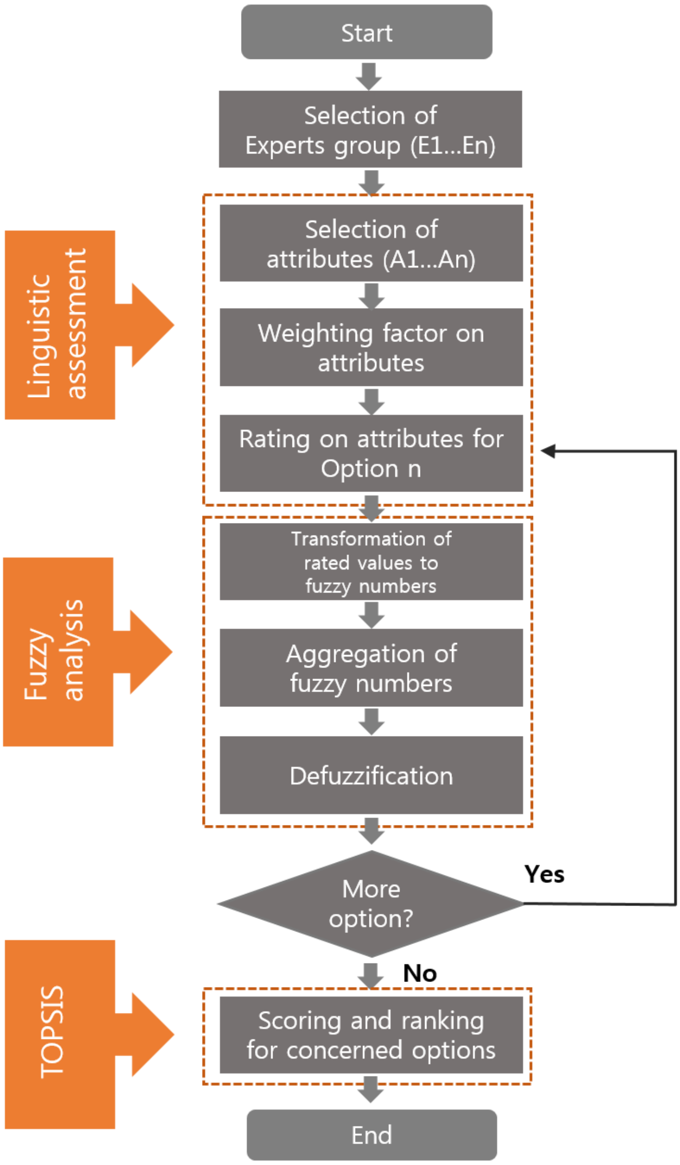


Fig. 8. Outline of the proposed approach on investigating the technical impact.

To investigate the technical impacts of the selected engine systems, this paper carried out surveys where four former on-board marine engineers with more than ten-year experience in this field. More importantly, the selected experts are direct stakeholders who have participated in the actual project that motivated this research. Also, the experts were the representative of each stakeholder group who was actually supposed to make the right decision for engine selection: class surveyor (E1), maritime professor (E2), marine engineering researcher (E3) and ship-owner (E4). The group of experts were subject to offer the performance rating on six different attributes across the ship's lifecycle as presented in Table 4.

Table 4

The technical attributes applied to fuzzy-TOPSIS

Ship phase	Attributes	Description
Contraction and decommission	Physical impact (A1)	the quality of system design, shape, mechanism and the intimacy with marine vessels
Operation	Reliability (A2)	the level of providing redundancy in preparation for a single failure
	Training (A4)	operators' confidence, knowledge and familiarisation in systems
	operability (A5)	the level of easiness and convenience in system operation
Maintenance	Management commitment (A3)	the level of time and efforts to be made for system maintenance and repair
	Safety (A6)	the level of potential risk caused by a system failure

Experts' preference was expressed by placing different levels of weights on each attribute. The weights range from 0 to 100 (corresponding to '*the least important*' and to '*the most important*' respectively).

To assess the attributes, five different rating categories were employed in linguistic terms: '*very low*', '*low*', '*medium*', '*high*' and '*very high*'. The scale of '*very high*' was regarded to be the most positive remark and the opposite was also true. The linguistic values obtained from the experts were transformed into trapezoidal fuzzy numbers following Table 5 (Chen and Hwang 1992; Lazakis and Ölçer 2016).

Table 5

Fuzzy numbers for five linguistic scales.

Scale	Fuzzy numbers
Very low	(0, 0, 0.1, 0.2)
Low	(0.1, 0.2, 0.2, 0.4)
Medium	(0.4, 0.5, 0.5, 0.6)
High	(0.7, 0.8, 0.8, 0.9)
Very high	(0.8, 0.9, 1, 1)

In general, the trapezoidal fuzzy number can be defined as $\tilde{m}$= (a,b,c,d) which is given by Eq. (3) (Zheng et al. 2012; Soheil and Kaveh 2010).

$$\mu_{\tilde{m}} = \begin{cases} 0 & (x < a) \\ \dfrac{x-a}{b-a} & (a \le x \le b) \\ 1 & (b \le x \le c) \\ \dfrac{d-x}{d-c} & (c \le x \le d) \\ 0 & (x > d) \end{cases} \tag{3}$$

Where,

[b, c]	mode intervals of $\tilde{m}$
[a, d]	lower and upper limits of $\tilde{m}$
$\mu_{\tilde{m}}$	membership function of $\tilde{m}$

The aggregation of trapezoidal fuzzy numbers can be made with the operational laws through Eqs (4)- (9) as described below:

$$\tilde{A}(+)\tilde{B} = (a_1,b_1,c_1,d_1)(+)(a_2,b_2,c_2,d_2) = (a_1+a_2,b_1+b_2,c_1+c_2,d_1+d_2) \tag{4}$$

$$\tilde{A}(-)\tilde{B} = (a_1,b_1,c_1,d_1)(-)(a_2,b_2,c_2,d_2) = (a_1-a_2,b_1-b_2,c_1-c_2,d_1-d_2) \tag{5}$$

$$\tilde{A}(\otimes)\tilde{B} = (a_1,b_1,c_1,d_1)(\otimes)(a_2,b_2,c_2,d_2) = (a_1 \cdot a_2, b_1 \cdot b_2, c_1 \cdot c_2, d_1 \cdot d_2) \tag{6}$$

$$\tilde{A}(\phi)\tilde{B} = (a_1,b_1,c_1,d_1)(\phi)(a_2,b_2,c_2,d_2) = (\frac{a_1}{a_2}, \frac{b_1}{b_2}, \frac{c_1}{c_2}, \frac{d_1}{d_2}) \tag{7}$$

$$k\tilde{A} = (k \cdot a_1, k \cdot b_1, k \cdot c_1, k \cdot d_1) \tag{8}$$

The aggregated fuzzy numbers $\tilde{A} = (a,b,c,d)$, can return to the crisp values through defuzzification process (Zheng et al. 2006).

$$N = \frac{(a+2b+2c+d)}{6} \tag{9}$$

To evaluate the technical impacts of each option, the TOPSIS method was applied. Firstly, the crisp values obtained from the defuzzification can be normalised based on Eq. (10).

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{N} x_{ij}^2}} \;\; ; j=1, 2, ..., m ; i=1, 2, ..., n \tag{10}$$

Where, i is the number of options; j is the number of attributes.

Then, the factors, which had been pre-assigned by the experts, were weighted on the normalised values of each attribute as shown in Eq. (11).

$$v_{ij} = w_j r_{ij} \;\; ; j=1, 2, ..., m ; i=1, 2, ..., n \tag{11}$$

Where, w_j represents the weight of the j^{th} attribute.

To determine the ideal and nadir ideal solutions, the ideal values set and the nadir values set were determined as described in Eqs (12) and (13).

$$\{v_1^+, v_2^+, ..., v_n^+\} = \{(\max v_{ij} \,|\, j \in k), (\min v_{ij} \,|\, j \in k') | \;\; ; i=1, 2, ..., m\} \tag{12}$$

$$\{v_1^-, v_2^-, ..., v_n^-\} = \{(\min v_{ij} \big| j \in k), \ (\max v_{ij} \big| j \in k') \big| \ ; i=1, 2, ..., m\} \tag{13}$$

Where, k is the index set of benefit attributes and k' is the index set of cost attributes.

Based Eqs (14) and (15), the two Euclidean distances for each option were calculated.

$$S_i^+ = \left\{ \sum_{i=1}^{n} (v_{ij} - v_j^+)^2 \right\}^{0.5} \quad ; j=1, 2, ..., m \ ; i=1, 2, ..., n \tag{14}$$

$$S_i^- = \left\{ \sum_{i=1}^{n} (v_{ij} - v_j^-)^2 \right\}^{0.5} \quad ; j=1, 2, ..., m \ ; i=1, 2, ..., n \tag{15}$$

Calculate the relative closeness to the ideal solution. The relative closeness to the ideal solution can be determined as shown in Eq. (16).

$$C_i^+ = \frac{S_i^-}{S_i^+ + S_i^-} \ ; i=1, 2, ..., n \ ; 0 \le C_i \le 1 \tag{16}$$

Finally, the most appropriate strategy will be indicated where is with the highest C_i^+. On the other hand, economic and environmental impacts were described as costs where higher value is negatively desired.

2.5.4. Multi-criteria decision making (Fuzzy AHP)

The results of the impact assessment makes the final decision-making process using fuzzy AHP to be ready. The normalisation process converts each impact expressed in various units into a single compatible ratio (%).

In order to reflect the priorities of decision-makers, it applies AHP technique which is renowned for a subjective weighting method or the pair-wise comparison model for determining the weights of each criterion. The matrix of the pair-wise comparisons for n criteria can be expressed as Eq. (17) (Wang et al. 2009).

$$\tilde{A}^k = \begin{bmatrix} \tilde{a}_{11}^k & \tilde{a}_{12}^k & \cdots & \tilde{a}_{1i}^k \\ \tilde{a}_{21}^k & \tilde{a}_{22}^k & \cdots & \tilde{a}_{2i}^k \\ \vdots & \vdots & & \vdots \\ \tilde{a}_{j1}^k & \tilde{a}_{j2}^k & \cdots & \tilde{a}_{ji}^k \end{bmatrix} \text{ ; j=1, 2, ..., m ; i=1, 2, ..., n} \tag{17}$$

Where, $\tilde{a}_{mn}^k$ represents the kth decision maker's preference of nth criterion over mth criterion.

The average preferences for each decision maker are calculated as in Eq. (18).

$$\tilde{a}_{ji} = \frac{\sum_{K=1}^{K} \tilde{a}_{ji}^k}{K} \text{ ; j=1, 2, ..., m ; i=1, 2, ..., n} \tag{18}$$

The geometric mean of fuzzy comparison values of each criterion is derived from Eqs (19-20) (Zheng et al. 2012).

$$\tilde{\alpha}_j = \left(\prod_{j=1}^{m} l_{ji}\right)^{1/m} \text{ ; } \tilde{\beta}_j = \left(\prod_{j=1}^{m} m_{ji}\right)^{1/m} \text{ ; } \tilde{\gamma}_j = \left(\prod_{j=1}^{m} n_{ji}\right)^{1/m} \text{ ; } \tilde{\delta}_j = \left(\prod_{m=1}^{m} s_{ji}\right)^{1/m} \tag{19}$$

$$\tilde{\alpha} = \sum_{j=1}^{m} \tilde{\alpha}_j \text{ ; } \tilde{\beta} = \sum_{j=1}^{m} \tilde{\beta}_j \text{ ; } \tilde{\gamma} = \sum_{j=1}^{m} \tilde{\gamma}_j \text{ ; } \tilde{\delta} = \sum_{j=1}^{m} \tilde{\delta}_j \tag{20}$$

Then the weights can be obtained as described in Eq. (21).

$$\tilde{w}_j = (\tilde{\alpha}_j \cdot \tilde{\delta}^{-1}, \tilde{\beta}_j \cdot \tilde{\gamma}^{-1}, \tilde{\gamma}_j \cdot \tilde{\beta}^{-1}, \tilde{\delta}_j \cdot \tilde{\alpha}^{-1}) \text{ ; j=1, 2, ...m} \tag{21}$$

The defuzzification of those fuzzy numbers was made by Eq. (22) (Ayhan 2013; Chou and Chang 2008).

$$M_j = \frac{\tilde{\alpha}_j \cdot \tilde{\delta}^{-1} + \tilde{\beta}_j \cdot \tilde{\gamma}^{-1} + \tilde{\gamma}_j \cdot \tilde{\beta}^{-1} + \tilde{\delta}_j \cdot \tilde{\alpha}^{-1}}{4} \tag{22}$$

Where, M_j represents defuzzifed value for the criterion j^{th}.

Finally, the normalisation is processed with Eq. (23) (Ayhan 2013).

$$N_j = \frac{M_j}{\sum_{j=1}^{m} M_j} \tag{23}$$

Where, N_j represents the final weight for the criterion j^{th}.

Lastly, a sensitivity analysis was carried out to identify the influence of weighting factors on the final decision with three different stakeholder groups: environmentalists, economists and engineers.

To assess the decision makers' preferences, five different scales for relative rating importance were used in linguistic terms: *'equally important'*, *'weakly important'*, *'fairly important'*, *'strongly important'* and *'absolutely important'*. The linguistic values obtained from the experts were transformed into trapezoidal fuzzy numbers in accordance with Table 6 (Chen and Hwang 1992; Lazakis and Ölçer 2016).

Table 6

Fuzzy numbers for five linguistic scales.

Linguistic variable	A scale of relative importance	Fuzzy Trapezoidal number
Equally important	1	(1, 1, 1, 1)
Weakly important	3	(2, 2.5, 3.5, 4)
Fairly important	5	(4, 4.5, 5.5, 6)
Strongly important	7	(6, 6.5, 7.5, 8)
Absolutely important	9	(8, 8.5, 9, 9)
x=2,4,6,8 are intermediate scales (x-1, x-1/2, x+1/2+1)		

3. Case study

Amid a rapid change in the world energy market, Korea Gas Corporation (KOGAS) was committed to diversify the source of the LNG suppliers which had been overly relied on the Middle East. As a result, it has successfully signed several new projects, such as an Australian GLNG project and a US Sabine Pass LNG, to secure the long term energy supply. It was reported that KOGAS would purchase about 6.3 million tons of LNG annually from the two projects, which claimed 8 new LNG carriers having 147,000 m^3 cargo capacity to be constructed. The project of building new LNG carries has undergone a rigorous technical review and decision-making processes to identify the best choice across the credible engine systems before the conceptual design was complete.

The case study pertinent to this paper started from this background. Hence, it was designed to investigate the strengths and the limits of the credible engine systems as described in Section 1.2 from the economic-environmental-technical perspectives. The proposed method discussed in Section 2 was applied to evaluate the optimistic engine system in a holistic view.

3.1. Data collection

Fig. 9 shows a brief outline of data collection from stakeholders: mainly, the ship-owner, operators, engine manufacturers, shipyards and marine engineering experts. The collected data was thoroughly analyzed by the project team as a third party in an effort to properly select the engine system for a series of new vessels.

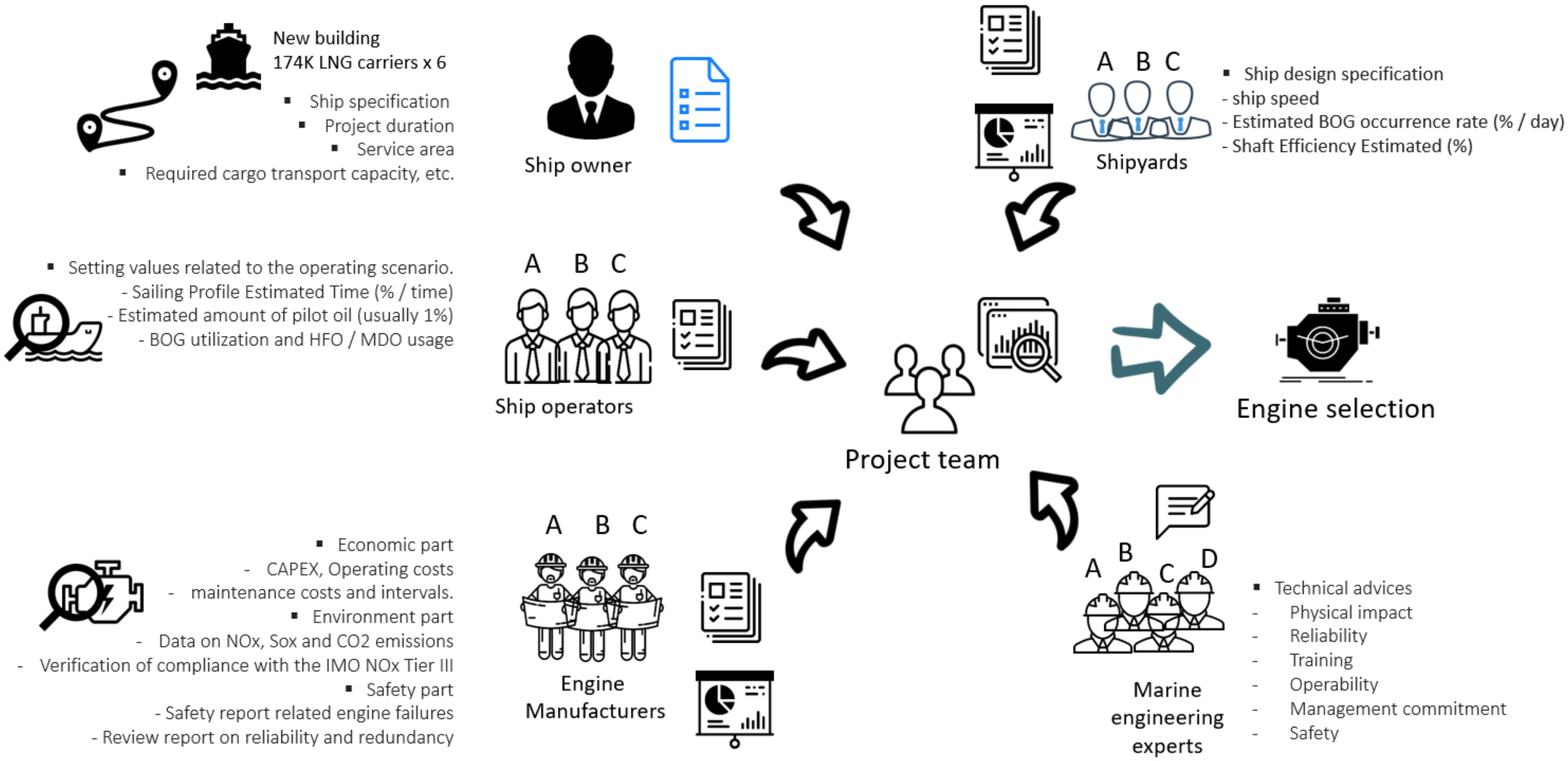


Fig. 9. Outline of date collection.

3.2. *Case ship*

3.2.1. *Description of ship particulars and voyage information*

Given that the LNG import was estimated at 2,800,000 tons annually from Sabine Pass between 2017 and 2037 (20 year project period), Fig. 10 shows the basic information of the case ship and its routine voyage between Incheon, South Korea and Sabine Pass, USA.

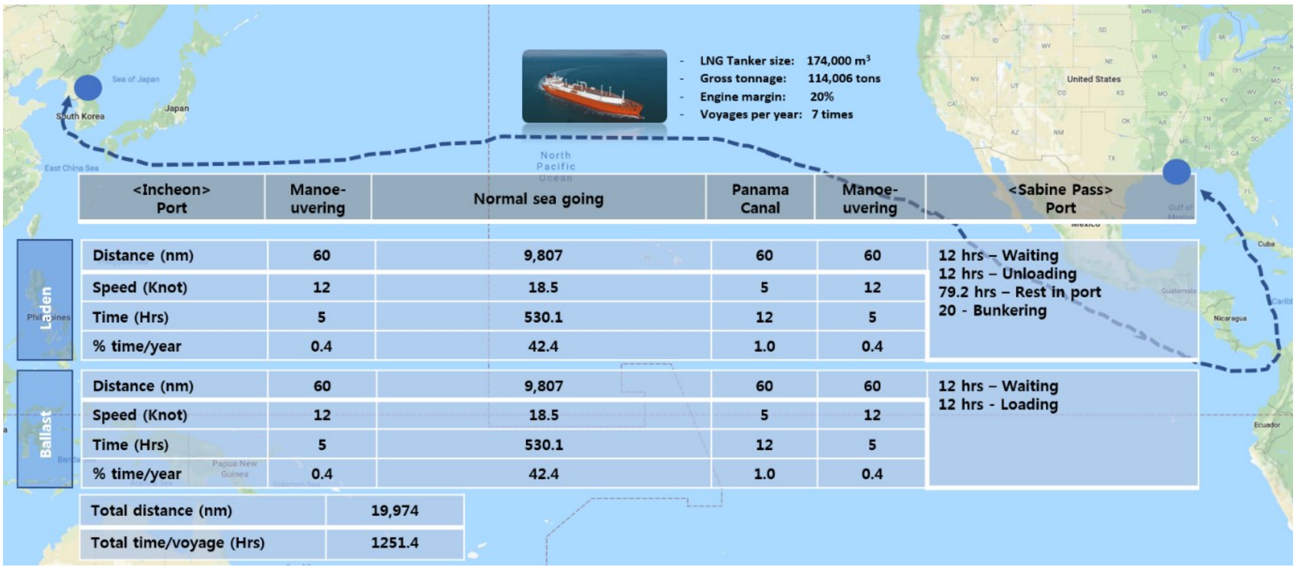


Fig. 10. Information of case ship and voyage (KOGAS 2013).

3.2.2. *Application of the engine systems*

Table 7 summarises the configuration of each engine system which was specifically modelled in accordance with the specification of the case ship. This conceptual design work was performed and validated during the actual project.

<u>*UST*</u>

By using the external combustion principle, the high pressure steam generated from the UST is used to rotate the gearbox connected to the propeller. Two sets of turbine generators are to be installed to supply electricity to the vessel. UST does not require specific fuel supplying systems and excess BOG, if any, can be consumed in the main boilers with steam dumping.

FME

Four FME sets were arranged in parallel so that the electricity generated by the engine could be delivered to the primary consumer. Electric power is supplied to the electric motor installed on the propeller in the electric hub, which is called the Main Switchboard. Parts of electricity from FMEs are also provided for electrical consumers and auxiliary systems.

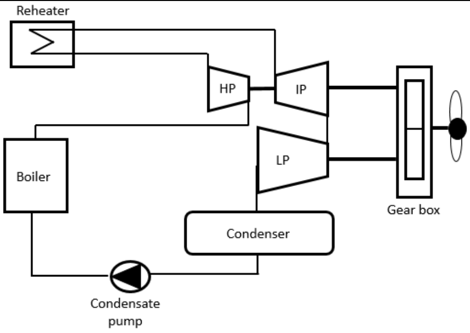
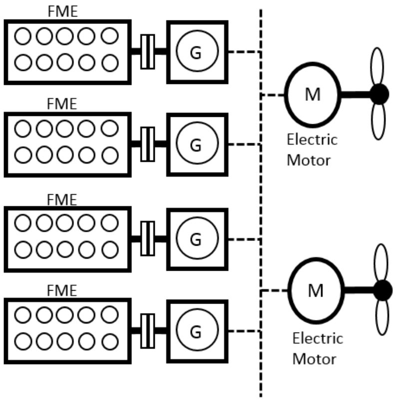
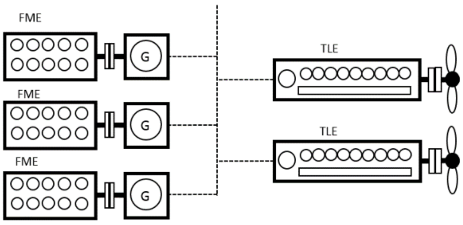
TLE

Unlike FMEs, two TLEs adopt the mechanical propulsion principle in which the physical engine power is directly transmitted through the shafts which are coupled with the propellers. Three sets of generators are to be additionally added in response to electricity loads.

This case study was assumed that the all proposed engine systems would be operated in gas mode where using BOG as fuel. However, for the internal combustion engines in gas mode, FMEs and TLEs require to use MGO or HFO as a pilot fuel (a starting fuel) accounting for less than 1 % of BOG usage. On the other hand, FME and TLE are equipped with a fuel gas supply system (FGSS), which is a compact module mainly composed of pumps and heaters.

Table 7

The configuration of proposed engine systems for case ship.

Engine type	Outlines	Composition	-BOG handling	Power transmission	Generator engines	Fuel used
UST		High-pressure boiler (2 sets) High, medium & low-pressure turbine	- Burning on boilers - Steam dumping	Reduction gear	T/G (2 sets) D/G (for emergency)	HFO and /or Gas No pilot oil
FME		Medium Speed Diesel (4 sets)	- Burning in the engine - Oxidizer	Electric propulsion	NIL	HFO and /or Gas MGO for pilot oil
TLE		Slow Speed Diesel (2 sets)	- Burning in the engine - Oxidizer	Mechanical shaft	G/E (3 sets)	HFO and /or Gas MGO for pilot oil

3.3. *Results of analysis*

3.3.1. *Economic impact*

Table 8 presents the summary of life cycle cost estimates according to the different engine systems.

Table 8

Summary of economic impact estimates.

<table>
<tr><th></th><th>Items</th><th>UST</th><th>FME</th><th>TLE</th></tr>
<tr><td rowspan="8">Construction</td><td>Gensets (includes redundancy)</td><td>5.3</td><td>15.8</td><td>5.0</td></tr>
<tr><td>Main Engine</td><td rowspan="6">Main turbine
Main boiler
Main turbine
Feed water pump
& turbine
Generator turbine</td><td>-</td><td>10.5</td></tr>
<tr><td>Electrical systems</td><td>8.0</td><td>1.5</td></tr>
<tr><td>Fuel Gas Supply</td><td>2.0</td><td>8.0</td></tr>
<tr><td>Gearbox</td><td>1.5</td><td>-</td></tr>
<tr><td>Spare parts</td><td>2.0</td><td>0.5</td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td>Total budget price USD</td><td>26.5</td><td>29.3</td><td>25.5</td></tr>
<tr><td rowspan="9">Operation</td><td>LNG (tonnes/yr)</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>BOG (tonnes/yr)</td><td>38,184</td><td>34,905</td><td>28,360</td></tr>
<tr><td>MGO (tonnes/yr)</td><td>-</td><td>-</td><td>1,296</td></tr>
<tr><td>MDO (tonnes/yr)</td><td>-</td><td>385</td><td>48</td></tr>
<tr><td>BOG (M$/yr)</td><td>22.9</td><td>20.9</td><td>17.0</td></tr>
<tr><td>MGO(M$/yr)</td><td>0.0</td><td>0.0</td><td>1.3</td></tr>
<tr><td>MDO (M$/yr)</td><td>0.0</td><td>0.4</td><td>0.0</td></tr>
<tr><td>Lube oil (M$/yr)</td><td>0.0</td><td>0.1</td><td>0.1</td></tr>
<tr><td>Sum</td><td>23</td><td>21</td><td>18</td></tr>
<tr><td>Maintenance</td><td>Maintenance (M$/yr)</td><td>0.2</td><td>1.2</td><td>0.7</td></tr>
<tr><td>Decommission</td><td>Recycling benefits (M$)</td><td>-0.06</td><td>-0.05</td><td>-0.11</td></tr>
</table>

The costs of engine systems in the construction phase was estimated with the help of representative engine manufacturers. The engine configuration with FMEs was found to be relatively expensive ($ 29.3M), whereas the TLE equivalence was generous ($ 25.5M). The UST was costed between the two internal engine systems: $ 26.5M.

High initial costs for FMEs seem to be influenced by the system complexity based on the fact that the electric propulsion system adopted by the FMEs required an intermediate system to convert mechanical power to electricity, while the TLEs could use direct mechanical power for propulsion. Also, the UST requires an intermediate system to convert steam power to mechanical one, but this process is relatively simple compared to electric propulsion.

The operational costs of engine systems are directly related to the system efficiency. The TLEs are known to have better performance than other two types, which are smoothly revealed with the results of economic assessment. On the other hand, despite a significant upgrade, the UST was still less efficient, which claimed higher level of fuel consumption, thereby operating costs.

Assessment results revealed that the 20-year operating costs would account for the largest part of the economy impact.

While there would be more than a few maintenance items, this paper directly adopted the annual maintenance costs provided by the engine manufacturers (KOGAS 2013; MHI 2013). Therefore, the following maintenance costs were assigned to the analysis: UST is $0.2 M/year; FME is $1.2 M/year; TLE is $0.7 M/year. The UST was found to be the most cost-effective regarding maintenance viewpoint than the internal combustion engine systems. This is because maintenance of the external combustion engine system is relatively handy and the number of spare parts to be replaced regularly is low. The FMEs were shown to require higher maintenance costs than the TLEs because the maintenance intervals are frequent and there are more spare parts than the others.

Unlike the other ship life stages, the decommission phase can be characterised as an economic benefit from material recycling, rather than expense. Table 9 shows the types and amount of recycling materials for each engine system.

Table 9

Recycling materials for engine systems (Jeong et al. 2018a; Scania, 2016).

<table>
<tr><th>Engine type</th><th>Materials</th><th colspan="2">Each weight (ton)</th><th>Total weight (ton)</th></tr>
<tr><td rowspan="2">UST</td><td>Steel</td><td colspan="2">178.6</td><td rowspan="2">About 380.0</td></tr>
<tr><td>Cast iron</td><td colspan="2">201.4</td></tr>
<tr><td rowspan="4">FME (4 sets)</td><td>Steel</td><td colspan="2">74.0</td><td rowspan="4">About 185.0</td></tr>
<tr><td>Cast iron</td><td colspan="2">85.1</td></tr>
<tr><td>Aluminium</td><td colspan="2">14.8</td></tr>
<tr><td>Plastic</td><td colspan="2">1.665</td></tr>
<tr><td rowspan="5">TLE (M/E 2sets)
FME (G/E 3 sets)</td><td>-</td><td>M/E</td><td>G/E</td><td rowspan="5">M/E about 350 .0
G/E about 44.0</td></tr>
<tr><td>Steel</td><td>140</td><td>17.6</td></tr>
<tr><td>Cast iron</td><td>161</td><td>20.24</td></tr>
<tr><td>Aluminium</td><td>28</td><td>3.52</td></tr>
<tr><td>Plastic</td><td>3.15</td><td>0.396</td></tr>
</table>

The results of the holistic economic evaluation taking account of the discount rate are summarised in Fig. 11 which shows the cumulative cost over the ship's lifecycle.

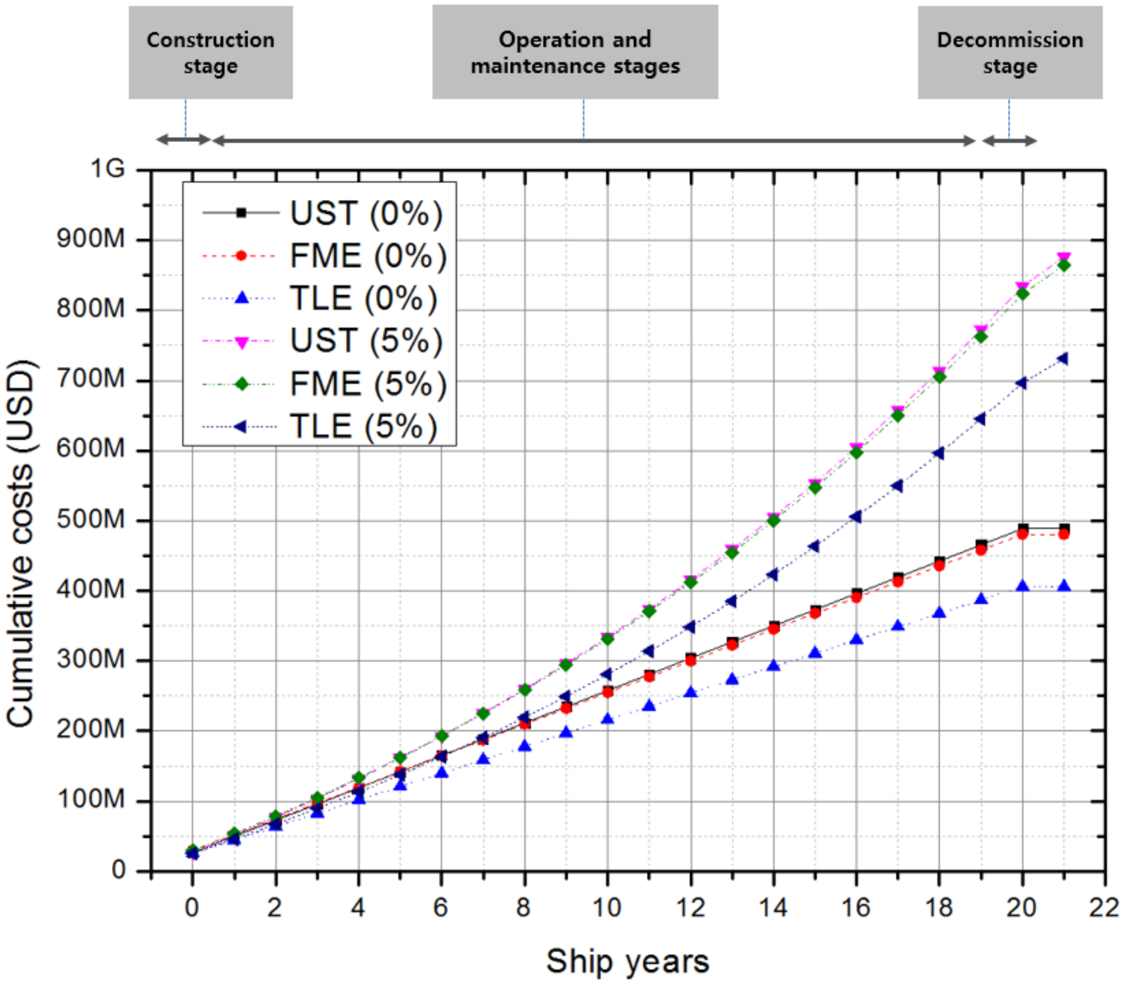


Fig. 11. Cumulative costs for economic impact over ship life cycle.

3.3.2. Environmental impact

Table 10 shows the amounts of the representative emissions; by means of GaBi software, in accordance with CML 2001 and ILCD PEF, various types of emissions were converted into the five representative emissions as declared earlier.

Table 10

Summary of environmental impact estimates. (Unit: kg).

	UST				FMEs				TLEs			
Emissions	Construction	Operation	Scrapping	**Total**	Construction	Operation	Scrapping	**Total**	Construction	Operation	Scrapping	**Total**
CO_2 Eq.	5.31E+05	2.63E+09	5.30E+05	2.63E+09	9.52E+05	2.44E+09	9.52E+05	2.44E+09	1.07E+06	2.09E+09	1.07E+06	2.09E+09
NOx Eq.	1.85E+02	2.91E+06	1.81E+02	2.91E+06	3.34E+02	3.01E+06	3.24E+02	3.01E+06	3.76E+02	3.35E+06	3.64E+02	3.35E+06
NMVOC Eq.	6.43E+02	1.03E+07	6.30E+02	1.03E+07	1.16E+03	1.04E+07	1.13E+03	1.04E+07	1.31E+03	1.09E+07	1.27E+03	1.09E+07
SOx Eq.	1.03E+03	3.76E+06	1.03E+03	3.76E+06	1.86E+03	3.96E+06	1.85E+03	3.96E+06	2.09E+03	4.54E+06	2.08E+03	4.55E+06
$PM_{2.5}$ Eq.	6.99E+02	1.73E+05	6.98E+02	1.74E+05	1.19E+03	1.74E+05	1.19E+03	1.76E+05	1.34E+03	1.81E+05	1.33E+03	1.83E+05

Firstly, the results of the environmental analysis revealed that the emission level of CO_2 eq. was much higher than the other emission types. For example, the use of the UST system produced 2.63E+9 kg CO_2 eq. while emitting 2.91E+6 kg NOx eq., 1.03E+7 kg NMVOC eq., 3.76E+6 kg SO_x eq. and 1.74E+3 kg $PM_{2.5}$ eq.

Comparing the engine systems, the use of TLEs was revealed to reduce the emission of CO_2 eq. modestly, whereas the use of UST was shown to be the worst. This trend could be observed by the fact that the amounts of emissions generated were proportional to the amount of fuels used: as discussed previously, the UST proved to consume more fuel than the other options.

On the other hand, to be surprised, the UST was turned out the most optimistic in terms of the pollution levels of the other emission types: NO_x eq., NMVOC eq., SO_x eq. and $PM_{2.5}$ eq. Such a result was attributed to the adverse characteristics of internal combustion engines which require MGO or MDO to be consumed as pilot fuel. This finding indicates that the use of the conventional liquid fuels has significantly contributed to marine pollution.

In Fig. 12, the estimated emissions were converted into the monetary values.

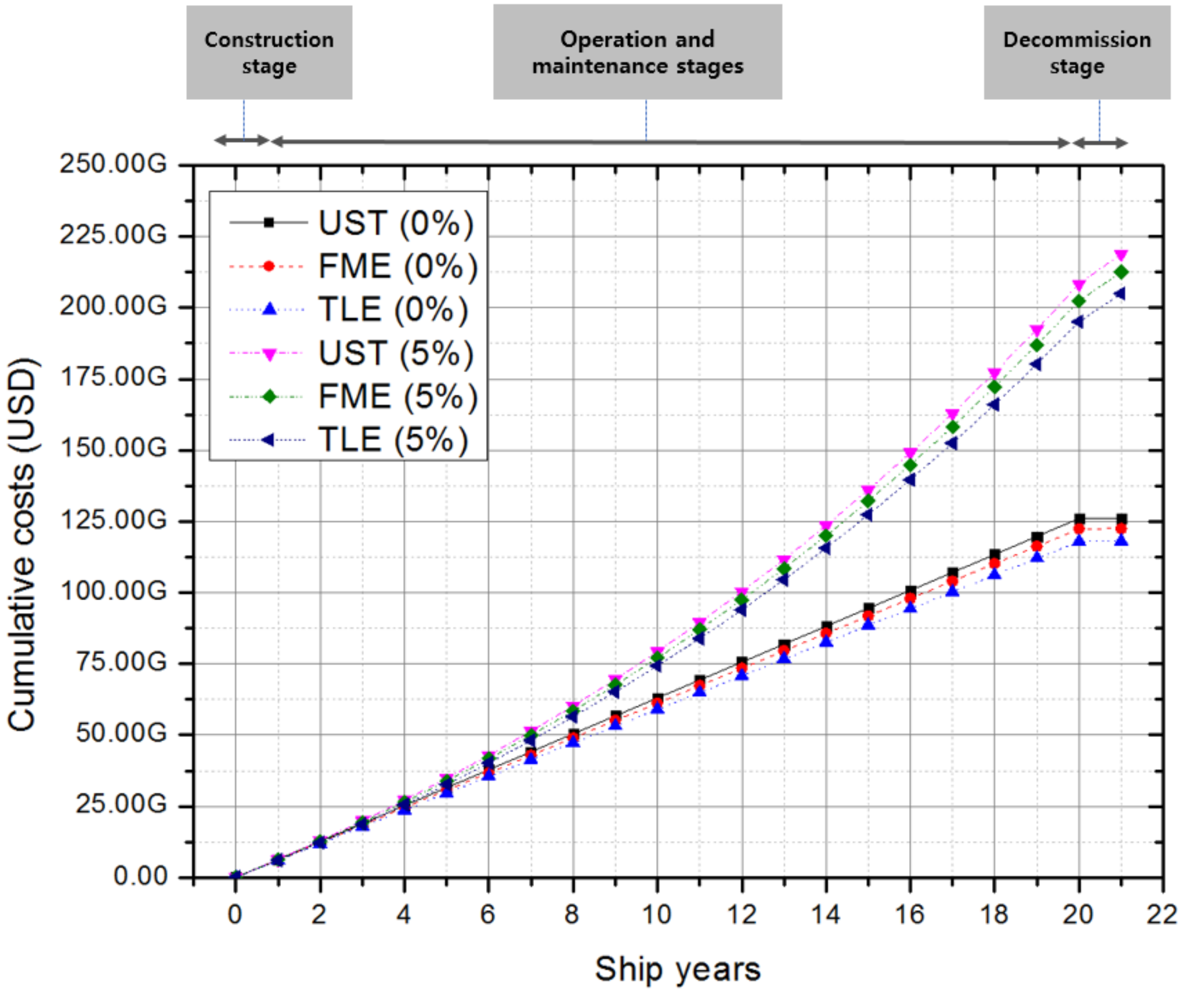


Fig. 12. Cumulative costs for environmental impact over ship life cycle.

3.3.3. *Technical impact*

From a technical standpoint, actual KOGAS project participants were invited to compare the performance of each engine type. The project team selected representatives from four stakeholder groups: engine builders, marine engineers, taxonomies and ocean professors.

A rigorous survey was conducted with the questionnaire distribution with the assigned experts. Then, their views on the six technical attributes were returned as shown in Table 11. To support their evaluation, general remarks from experts were summarised in Table 12.

Some remarkable points can be highlighted. Firstly, it was viewed that the compact systems of TLEs was expected to contribute to facilitating the arrangement of machinery space. On the other hand, the TLEs require additional safety verification for of the 300 bar high-pressure gas injection system. Secondly, the UST was considered to need to overcome the adverse characteristics of the steam turbine system with relatively low efficiency, particularly during manoeuvring. Besides, the complexity of the UST system arrangement also needs to be optimised. Lastly, the strengths of FMEs were placed on the lower risk of low gas pressure and reliable redundancy with good safety records.

Table 11

Summary of technical impact estimates.

Attributes /Solutions	E_1 (class surveyor)			E_2 (Maritime Professor)			E_3 (marine engineering researcher)			E_4 (ship-owner)		
	UST	TLE	FME	UST	TLE	FME	UST	TLE	FME	UST	TLE	FME
A_1 (Physical impact)	medium (0.3, 0.5,0.5,0.7)	very high (0.8, 0.9, 1, 1)	high (0.6, 0.75, 0.75, 0.9)	low (0.1, 0.25, 0.25, 0.4)	very high (0.8, 0.9, 1, 1)	high (0.6, 0.75, 0.75, 0.9)	low (0.1, 0.25, 0.25, 0.4)	very high (0.8, 0.9, 1, 1)	high (0.6, 0.75, 0.75, 0.9)	medium (0.3, 0.5,0.5,0.7)	high (0.6, 0.75, 0.75, 0.9)	very high (0.8, 0.9, 1, 1)
A_2 (Reliability)	low (0.1, 0.25, 0.25, 0.4)	high (0.6, 0.75, 0.75, 0.9)	very high (0.8, 0.9, 1, 1)	low (0.1, 0.25, 0.25, 0.4)	high (0.6, 0.75, 0.75, 0.9)	very high (0.8, 0.9, 1, 1)	medium (0.3, 0.5,0.5,0.7)	high (0.6, 0.75, 0.75, 0.9)	high (0.6, 0.75, 0.75, 0.9)	medium (0.3, 0.5,0.5,0.7)	medium (0.3, 0.5,0.5,0.7)	very high (0.8, 0.9, 1, 1)
A_3 (Management commitment)	very high (0.8, 0.9, 1, 1)	medium (0.3, 0.5,0.5,0.7)	low (0.1, 0.25, 0.25, 0.4)	very high (0.8, 0.9, 1, 1)	high (0.6, 0.75, 0.75, 0.9)	low (0.1, 0.25, 0.25, 0.4)	very high (0.8, 0.9, 1, 1)	high (0.6, 0.75, 0.75, 0.9)	high (0.6, 0.75, 0.75, 0.9)	very high (0.8, 0.9, 1, 1)	medium (0.3, 0.5,0.5,0.7)	medium (0.3, 0.5,0.5,0.7)
A_4 (Training)	very low (0, 0.1, 0.1, 0.2)	very high (0.8, 0.9, 1, 1)	very high (0.8, 0.9, 1, 1)	low (0.1, 0.25, 0.25, 0.4)	high (0.6, 0.75, 0.75, 0.9)	medium (0.3, 0.5,0.5,0.7)	medium (0.3, 0.5,0.5,0.7)	high (0.6, 0.75, 0.75, 0.9)	very high (0.8, 0.9, 1, 1)	medium (0.3, 0.5,0.5,0.7)	very high (0.8, 0.9, 1, 1)	high (0.6, 0.75, 0.75, 0.9)
A_5 (operability)	low (0.1, 0.25, 0.25, 0.4)	high (0.6, 0.75, 0.75, 0.9)	medium (0.3, 0.5,0.5,0.7)	medium (0.3, 0.5,0.5,0.7)	high (0.6, 0.75, 0.75, 0.9)	medium (0.3, 0.5,0.5,0.7)	low (0.1, 0.25, 0.25, 0.4)	high (0.6, 0.75, 0.75, 0.9)	high (0.6, 0.75, 0.75, 0.9)	medium (0.3, 0.5,0.5,0.7)	high (0.6, 0.75, 0.75, 0.9)	very high (0.8, 0.9, 1, 1)
A_6 (Safety)	high (0.6, 0.75, 0.75, 0.9)	low (0.1, 0.25, 0.25, 0.4)	medium (0.3, 0.5,0.5,0.7)	very high (0.8, 0.9, 1, 1)	low (0.1, 0.25, 0.25, 0.4)	medium (0.3, 0.5,0.5,0.7)	high (0.6, 0.75, 0.75, 0.9)	medium (0.3, 0.5,0.5,0.7)	high (0.6, 0.75, 0.75, 0.9)	high (0.6, 0.75, 0.75, 0.9)	very low (0, 0.1, 0.1, 0.2)	very high (0.8, 0.9, 1, 1)

Table 12

Summary of experts' view on the technical impact of each engine.

	UST	FMEs	TLEs
A1	- A complicated process of making steam through the boiler and injecting it into the turbine. - High engine room space requirement	- A relatively complex system in combination of main generator, motors and integrated automation systems. - Simple fuel gas management design: satisfying IMO Tier III on gas - Easier to handle with low pressure	- Compact space management leading to optimal cargo space design - Easy retrofitting of existing main engines to gas engines. - The additional requirement of the gas supply system for gas compression
A2	- Lack of redundant system due to a large installation capacity - If a critical component such as the main boiler fails, the propulsion is completely lost.	- Very high redundancy due to the operation of two independent motors, switchboards, and multiple engines. - High flexibility in fuel selections	- High redundancy with two main engines - However, if a critical component such as a main switchboard or gas engine fails, the propulsion can be lost. - High flexibility in fuel selections
A3	- A high advantage in maintenance expense - Easiness and infrequent maintenance intervals	- Frequent maintenance intervals with multiple engines and subsequent systems - A number of spare parts to be regularly renewed	- Frequent maintenance intervals
A4	- Low familiarity with ship engineers - Lack of operation records	- High familiarity with engineers; multiple uses for generator engines	- Proven familization on conventional engines.

A5	- Manoeuvring performance is poor due to characteristics of the steam turbine - Sophisticated control of steam systems with	- complex automation with complicated systems such as controls of main generators, main electric power generation, motors and integrated automation system. - Otte cycle control: ▪ Mixer ratio is important ▪ Knocking to be counted ▪ Methane slip (discharge of unburned gas) to be considered	- Relatively simple automation with compact systems - Diesel cycle ▪ Mixer ratio is not affected ▪ Less knocking ▪ Methane slip (discharge of unburned gas) can be ignored
A6	- A potential risk of handling high-pressure steam - No safety records	- Low risk with relatively low gas pressure - Good safety records	- the highest risk factors of high pressure (300 bar)

Fig. 13 presents the results of technical impact assessments across the engine systems utilising Fuzzy TOPSIS, providing a clear indication that TLEs should be technically the best choice.

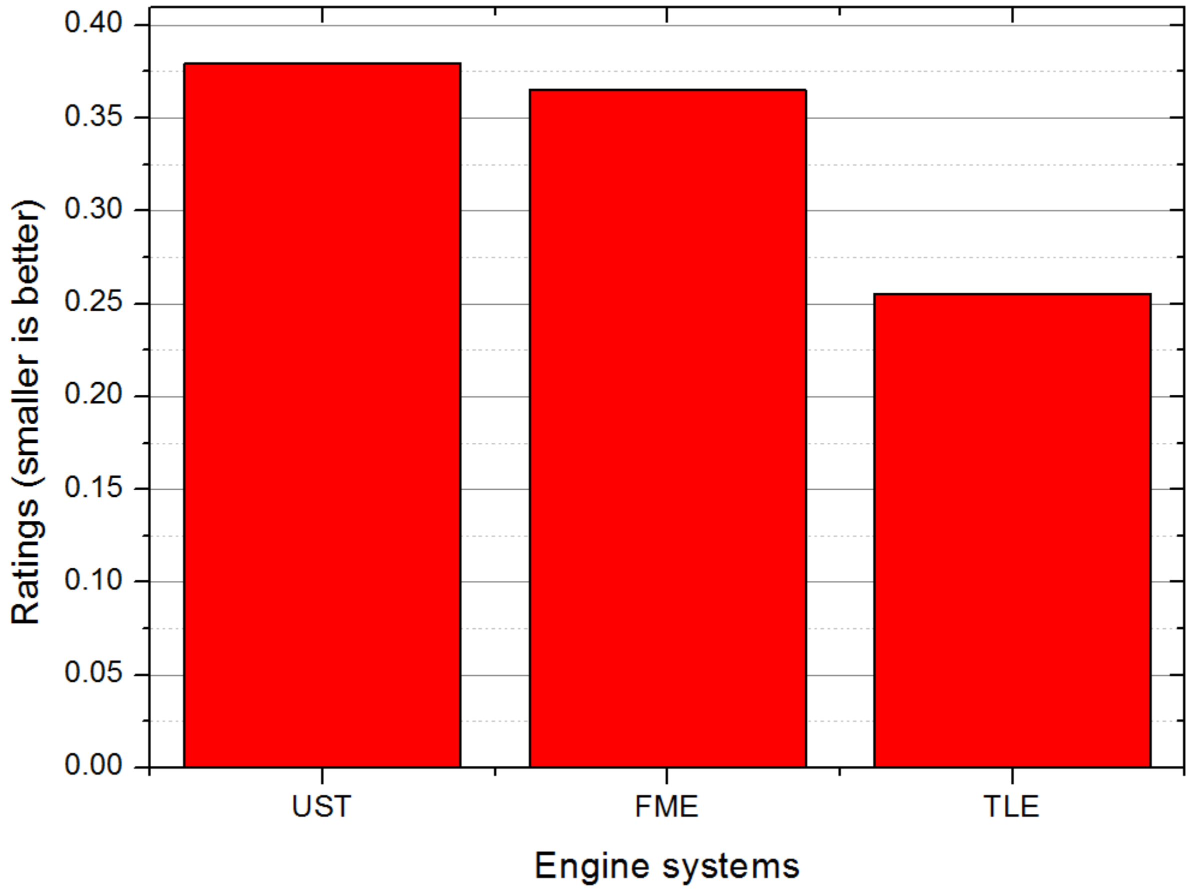


Fig. 13. Results of technical impact assessment.

3.4. Results of MCDM

As the last process, the impact values estimated throughout sections 3.2.1 to 3.2.3 were integrated employing Fuzzy AHP method where this paper assumed that three different decision-making groups: ship-operator, ship-owner (or manufacturer) and environmentalist.

In this case, rather than hiring experts groups, we set up a few cases that deliberately give different weighting levels on condition that different stakeholder groups have different preferences for weighting factors on the criteria. Hence, sensitivity analysis to investigate the weighting effect on the final outcomes was organised based on the following assumptions.

> The ship-operator would regard the technical impact fairly more important than two other impacts (Case 1); ship-owner (or manufacturer) considers the economic impact would be fairly more important than two other impacts (Case 2); environmentalist argues the environmental impact would be fairly more weighty than other two impacts (Case 3). Case 0 is assigned to be the importance of all impacts were equally treated.

As summarised in Fig. 14, MCDM results clearly suggested that the TLE option be ultimately better than two others in all cases. It also revealed that the performance of the FMEs be slightly better than that of the UST. Despite different weights across the cases, the final results were consistent.

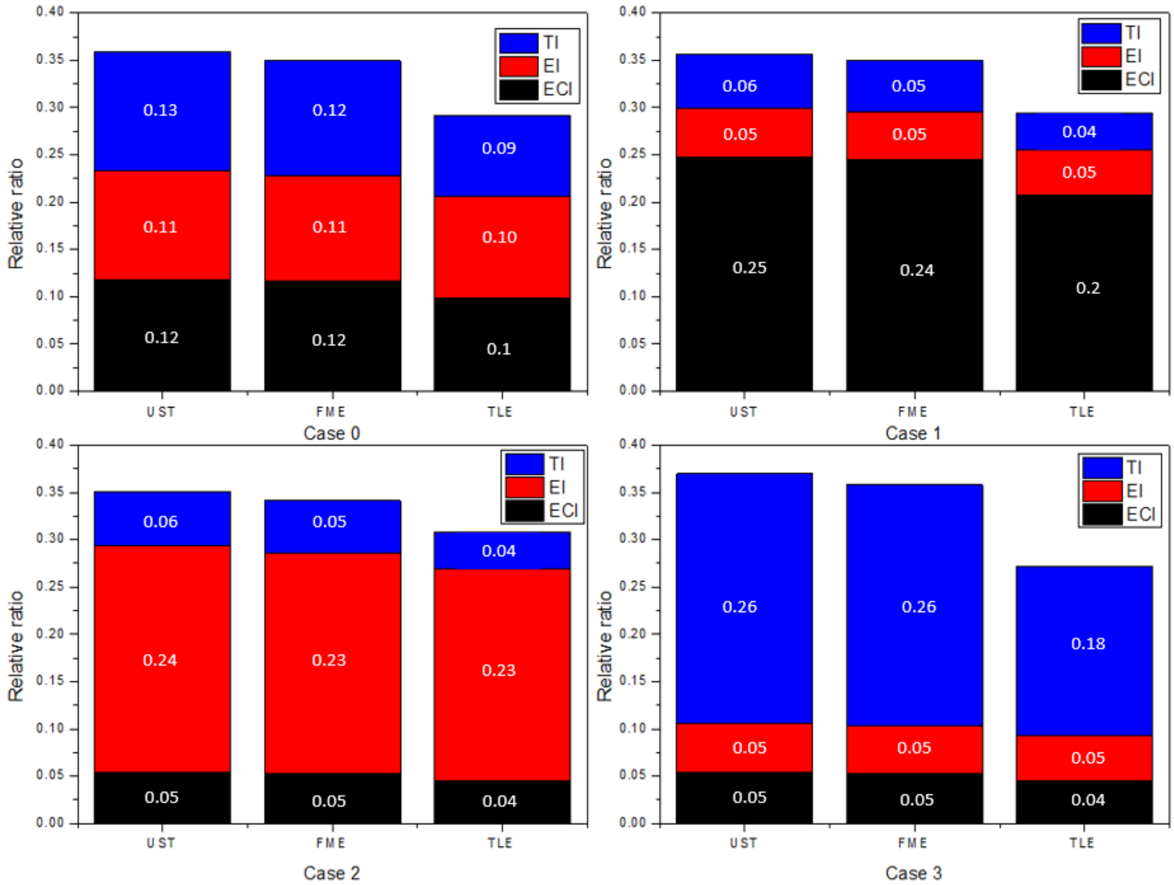


Fig. 14. Summary of MCDM results in various cases.

4. Discussion

Given that proper decision-making is paramount for the success of the business, this paper has been driven from the strong industrial need by the ship-owner (KOGAS) who strived to identify the optimal marine gas engine systems. To achieve this goal, we investigated economic, environmental and technical impacts and integrated them to make the best choice. Since the conventional MCDMs overly rely on qualitative assessments, thereby lacking the reliability, it was an essential process to develop a useful integration model as well as an enhanced MCDM quantitatively, leading to making a proper decision in the holistic view (Jeong et al. 2018). Evidently, the case study has proven the effectiveness of the proposed MCDM model by investigating the strengths and limits of the marine LNG engine systems. The functionality for sensitivity analysis has also shown to be excellent for understanding the consistency of the final outcomes.

Since maritime environmental regulations are getting stricter and stricter, the use of LNG as an alternative fuel is for sure a way forward. As discussing the strengths and the limits of current marine LNG engine systems, the research findings are believed to be a valuable guidance for ship designers and owners who are subjected to proper decision-making among various engine options. Also, the research results could be a modest indicator for anticipating the future trend of marine LNG engines. This paper also provides engine manufacturers with constructive recommendations on the places where their systems to be enhanced to build up the market competitiveness.

For a particular example, the Energy Efficiency Design Index (EEDI), which regulates the CO_2 emissions, has been applied to new vessels since January 1, 2015. In this context, the amount of CO_2 eq. generated by each engine type was the highest for UST at 2.63E+09 kg, and the TLEs and FMEs were similar at 2.44E+09 kg and 2.09E+09 kg, respectively. Therefore, to satisfy the EEDI, the ship selecting the UST as the propulsion engine needs to take more consideration of the fuel consumption and ship speed than the ships equipped with FMEs and TLEs.

Moreover, the 'IMO-Tier III' requirement (NO_x regulation) applied since 2016 cannot be overlooked. The only engine types that can satisfy 'IMO-Tier III' are the UST and the FMEs in gas mode, not diesel mode, at present. Therefore, when selecting the internal combustion engines, FMEs or TLEs, NO_x treatment systems such as selective catalytic reduction (SCR) should be additionally installed to satisfy the Tier III requirement. It is because the use of MDO or MGO increases the NO_x eq. emissions from FMEs and TLEs significantly. Meaningfully, the potential costs associated with environmental impacts were much higher than those related to economic impacts, which could be a good indicator of how seriously we are concerned about environmental conservation.

While a massive number of new marine systems are continuously flooding the industry, it becomes harder and harder for designers, operators and the service organisations to determine the best option across various alternatives. On the other hand, the existing regulations and practices have some limitations and gaps to examine the holistic cost, environmental and technical impacts of ship activities as well as marine systems. Given that LCA, MCDM and fuzzy techniques, which can remedy their shortcomings, are still under-used in the marine industry, the utilisation of the enhanced hybrid model has presented the usefulness of their combination, which will undoubtedly help stakeholders to obtain comprehensive views on more accurate and reliable decisions. In this context, this research also implied that the use of the structured guidelines of the enhanced hybrid MCDM could also be extended to various potential future studies for determining the best systems. Therefore, this paper, with the proposed MCDM model, is highly expected to contribute to improving the competitiveness of shipyards, ship-owners, operators, and manufactures by enhancing the sustainability of marine systems involved in construction, operation, maintenance and decommission.

Although this paper tested the proposed model for a marine case, there is no restriction on applying this model to various industrial studies that require appropriate decision making.

On the other hand, the proposed model does not fully address the problem of the human subjectivity inherent in MCDM as discussed in Sections 2.2 and 2.3. However, this model suggested that this limit could be reduced by pursing the quantitative approaches and performing the sensitivity analysis to evaluate the consistency of the final outcomes.

5. Conclusions

The novelty of this paper can be placed on developing a proper model and evaluating the performance of various marine LNG engine systems in multiple aspects. Throughout the process, the research work has presented a way to contribute to enhancing the sustainability of the marine industry.

Based on the research work discussed in this paper, the following conclusions can be drawn:

1) There is an urgent need for a systematic investigation of the performance of newly-introduced marine LNG engine systems. Key concerns in this analysis include economic, environmental and technical aspects.
2) The enhanced hybrid MCDM model was developed and applied to a case study to demonstrate that it is a more objective and quantitative approach than conventional qualitative methods for proper decision-making.
3) In examining the performances of three different marine LNG engine systems, research findings ultimately suggested that the TLEs would be the best option across them. There are some key outcomes to be discussed in detail:
    - The use of TLEs was found the most economical choice, thanks to its high propulsion efficiency which could significantly reduce the fuel consumptions during the operational phase.
    - The use of TLEs was also proven the best option concerning minimising CO_2 eq. emissions while the use of UST was shown to be optimistic for reducing the other concerned emissions.
    - The most favourable engine type concerning technical impact was also considered

as TLEs, but FMEs were noted for its exceptional stability and safety.

4) Despite a much higher degree of confidence, the relative complexity of this comprehensive model may diminish our passion to take advantage of this approach while adhering existing simple approaches. Developing a computational tool to facilitate this proceedings may be a tremendous asset for the future work. Lastly, to make a greater contribution to the industry, it may be essential to conduct more extensive and systematic studies with the proposed model.

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