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Research Article

Economic feasibility of LNG fuel for trans ocean-going ships: A case study of container ships

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Abstract
The challenges and risks brought by the new 2020 sulfur cap are undeniable. Since the idea of using Liquefied Natural Gas (LNG) as a marine fuel for ocean-going ships has become more attractive to the industry, in this study, a lifetime-based cost evaluation framework is proposed to systematically evaluate the implementation of using LNG as fuel for general ocean-going commercial ships. This approach can be represented as a quantitative decision-supporting process with a combination of very different features of the economic aspect in one coherent framework. The benefits of the approach are discussed through a case study, and the economic performance of the 3 varying sizes of ocean-going LNG-fueled container ships are tested. The case study results indicate that, considering the differences in the life cycle cost (LCC) and cash flow performances between LNG-fueled ships and conventional oil-fueled ones, the acquisition premium for ocean-going LNG-fueled container ships is sufficient to warrant the saving in terms of the LCC. However, the LNG price differences in the different regions could lead to noticeable differences in LCC results. This study's analysis fills gaps identified in the existing research about the benefits and disadvantages of using LNG as fuel for general ocean-going commercial ships. Finally, the study reveals an underlying novelty of the proposed framework to provide reliable decision supporting in investment by expanding the short-term perspective to a lifetime one.

1. Introduction

International shipping is now a significant contributor to atmospheric pollution. Most merchant ships today use Heavy Fuel Oil (HFO), making the industry the single largest emission source for Nitrogen Oxide (NO), Sulfur Oxide (SO), and particulate matter (PM) in the transport sector. In response, by 2020, the International Convention for Prevention of Pollution from Ship (MARPOL), adopted by the International Maritime Organization (IMO), will mandate a global sulfur content cap on bunker fuel of 0.5 %, reduced from the current 3.5 % cap (IMO, 2016). Given the tightening emission control regulations, there is an increasing interest in using Liquefied Natural Gas (LNG) as a marine fuel.

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Table 1 MARPOL Annex VI progressive sulfur limits, showing reduction points for Sulfur Emission Control Areas (SECAs) and global limits.

MARPOL Annex VI sulfur limits			
SECA		**Global**	
2008	1.5 %	2008	4.5 %
2009	1.0 %	2012	3.5 %
2015	0.1 %	2020	0.5 %

The increasing interest in LNG as a marine fuel today is largely attributed to regulatory initiatives that focus on sulfur-related emissions from ships. LNG, as a leading alternative fuel that is acknowledged as the cleanest fossil fuel, has major superiorities in comparison with other conventional fossil fuels. The noteworthy potential in emission reduction and the attractive price mean that this alternative fuel has received increasing attention from shipowners and operators in the recent decade. The drive to use LNG as marine fuel today mainly come from the environmental and economic aspects.

1.1 Environmental drive for using LNG as fuel

In particular, the absence of sulfur content makes LNG one of the most promising alternative fuels in the shipping industry regarding the increasingly stringent emission control legislation. The upcoming environmental policies, such as the global 2020 sulfur limits and CO_2 regulations for international shipping, will play key roles in promoting the use of LNG fuel in the shipping industry. The chemical composition of LNG fuel offers great potential for the reduction of gas emissions from ships' operations. LNG typically comprises more than 95 % methane and ethane, with less than 5 % of other hydrocarbons (ethane, propane, and butanes) and nitrogen (API, 2015). The no-hydrocarbon components, such as mercury, oxygen, carbon dioxide, the sulfur compounds, and water, that are contained in the natural gas are generally removed from the liquefied process. In theory, there is practically no sulfur content associated with LNG combustion.

The idea of using LNG as a marine fuel has attracted wide attention from researchers, with comparative life cycle assessment-based studies of LNG fuel to traditional petroleum-based fuel in the maritime sector consistently demonstrating reductions in SOx and PM emission from LNG (Thomson et al., 2015; Banawan et al., 2009; Cheenkachorn et al., 2013; Chryssakis et al., 2014). This is generally observed in overall typical marine transport modes of long-haul cargo transport; short sea transport; and regional service vessels fueled with LNG. There is adequate evidence to show that switching to use LNG fuel can help to significantly reduce SO_x and PM emissions from a ship's operation Although, in real working, the components of LNG are slightly different from region to region, and may unavoidably contain micro sulfur-related impurity, the test data provided by DNV-GL (2011) show that switching from HFO to LNG fuel will help ships to achieve nearly a 100 % SO_x and PM reduction.

In an effort to further explore the advantages of LNG technology from an environmental perspective, the literature suggests a range of negligible to up to 90 % NO_x emission reduction when using LNG as fuel (Burel, Rodolfo, and Nicola, 2013; Kotwzan & Narewski, 2012). Stenersen and Thonstad (2017) tested 4 main gas engine types in the market, which were Lean-Burn Spark Ignited engines (LBSI-engine), Low Pressure Dual-Fuel engines (LPDF-engine), Low Pressure Dual-Fuel engines (LPDF-engine), and High-Pressure Gas Injection (HPDF-engine). As the result, compared to diesel operations, all 4 types of gas engine systems can help to achieve a more than 95 % reduction in SO_x emissions and one of more than 20 % in CO_2 emission. For the Lean-Burn and Low Pressure engine systems, ranges for the NO_x emission reduction were around 75 to 90 %. The experiences in Emission Control Area (ECAs) proved that LNG technology is the only available option that can meet, without any additional effort, both the 0.1 % sulfur limit and the Tier III NO_x limit.

Moreover, the noticeable performance in CO_2 reduction can help LNG-fueled ships comply more easily with the greenhouse gas (GHG) emission control requirement set by the IMO if the methane split from the combustion process can be effectively controlled. Switching to use LNG fuel may largely relieve the damage caused by ships to local and marine environments. The Netherlands Organization for Applied Scientific Research (TNO) carried out research in 2011; the study investigated the environmental aspects and, to a less extent, the economic aspects of using LNG as a marine fuel. The tank to propeller (TTP) result showed that the CO_2 emissions directly generated from LNG combustion are much lower than those for HFO and marine gasoil (MGO). The TTP CO_2 emission for the LNG case is 56.1 g/KJ, and for HFO and MGO are 77.3 and 74.0 g/KJ, respectively. However, when taking indirect CO_2 emissions into consideration (composed of CH_4 leakage and N_2O), the total TTP GHG emission of LNG-fueled vessels rises to 69.5g/MJ, a number only around 10 % lower than the TTP GHG emissions generated by conventionally-fueled oil vessels (Verbeek et al., 2011).

Table 2 Potential emission reduction with LNG operation.

Emission	Emission reduction with using LNG fuel compared with HFO	Environmental regulation
SO_x	100 %	Complies with ECA and 2020 global sulfur cap
NO_x LPDF-engine (Otto cycle)	75 - 90 %	Complies 2016 Tier III regulations in ECAs
NO_x HPDF engine (Diesel cycle)	40 %	EGR/SCR required to comply with ECA 2016 Tier III regulations
CO_2 (without CH_4 leakage)	25 - 30 %	Benefit for the EEDI requirement
PM	100 %	No regulation yet

It can be concluded, overall, from the literature reviewed above that switching to use LNG fuel can help to significantly reduce SO_x and PM emissions from a ship's operation, and has great potential for NO_x emission reduction when used in the Lean-Burn and Low-Pressure engine systems. Switching to use LNG fuel may largely relieve the damage caused by ships to local and marine environments. Also, with emission control regulations becoming stricter, at both the national and global level, the benefit in environmental performance will certainly increase willingness to use LNG as a marine fuel.

1.2 Economic drive for using LNG as fuel

Aside from environmental performance, the attraction of LNG fuel is also reflected in the economic aspect. The main benefit, from an economic viewpoint, of using LNG as fuel is considered to come from the price gap between LNG fuel and other low-sulfur-content fuels. Works which consider the impact of sulfur limits in MARPOL Annex VI, such as those of Notteboom (2011), Lindstad et al. (2014), and Schinas and Stefanakos (2013), highlight that switching to low sulfur fuel may significantly increase operational costs for shipping operators. Despite a fall in bunker prices from 2014, the average price of low sulfur content fuel oil (LSFO) in the main global ports is still around US$600 per ton. In contrast, average LNG prices in the past 2 decades are generally lower than alternative low sulfur fuel, and sometimes lower than the baseline heavy fuel oil price. The anticipated extra expense of low carbon fuels, relatively lower costs, and environmental performance make LNG an attractive option for shipping operators.

The advantages of LNG over other transportation fuels, and the major barriers to and uncertainties of LNG adoption, were discussed extensively in the literature. Incentivized by the development of the gas market and by the tightening of emission control requirements in the ECAs, the economic efficiency and feasibility of using LNG as fuel has received increasing attention from researchers. A summary of the economic-related studies that focus on using LNG as fuel in the regional market is provided in **Table 3**. Existing research has analyzed the performance of using LNG as fuel for ships but has used different focuses and methods- for example, looking variously at engine performance, a real-option model, the development of bunkering infrastructures, and bunkering methods. Most of the economic efficiency evaluation studies today target short sea ships (Ro-Ro, ferry, fishing ship, and LNG feeder ship) working within or spending a long time in the ECA zones. Strict emission control standards and easy to access LNG refueling make short sea ships the most promising sector for applying LNG fuel. The result of the literature review has revealed that, in terms of energy-price relationship, the potential benefit gained from the energy discount is sufficient to warrant the acquisition premium for using LNG fuel in ECAs. This makes LNG technology an economically feasible solution in ECAs.

After the IMO announced the global 0.5 % cap will be enforced from 2020, and without any delay, the option of using LNG as fuel has received increasing attention from shipowners and operators. The number of LNG-fueled ships and LNG infrastructure is increasing rapidly. According to statistical data, by the end of 2019, the total number of LNG-fueled ships in the global range reached 172, which was an increase of 20.3 % compared to 2018 (Yoo, 2019). Hence, recently, an increasing number of studies have focused on the performance of ocean-going LNG-fueled ships. Schinas and Butler (2016) addressed the bunking price issue for ocean-going LNG-fueled ships and proposed a methodology to evaluate the commercial incentives of using LNG as fuel. Cariou et al. (2019) and Xu and Yang (2020) assessed the potential cost saving and CO2 emission reduction of LNG-fueled container ships working along the Northern Sea Route. Tan et al. (2020) compared the fuel costs for different types of LNG/diesel dual fuel engines along 3 major liner routes in the Asia region. The results highlighted the importance of the LNG bunkering cost minimizing problem and the potential influence of LNG bunkering infrastructures and bunkering strategies on the bunkering costs and design of LNG-fueled ships. Li et al. (2020) investigated the public's willingness to pay (WTP) for products imported in LNG-fueled ships. These reviewed studies concerned the potential benefits of LNG-fueled ships in the economic and environmental aspects, the development of LNG bunkering infrastructures in the global range, LNG prices in different regions, and transparency; the results emphasized the uncertainties and challenges of using LNG as fuel for ocean-going ships. The industry today clearly calls for more detailed research on the economic performance of using LNG as a marine fuel, especially for ocean-going vessels such as tankers and container vessels.

Table 3 Summary of studies focusing on economic performance of using LNG as fuel.

Research target	**Small size ships**	**Handy-sized ships**	**Short sea and coastal shipping**	**Ferry ships and LNG feeder ships**	**Short sea and coastal shipping**
Working area	ECAs	ECAs	ECAs	Taiwan Strait	EU region
Year of the study	2015	2014	2016	2018	2018
Reference	Li et al., 2015	Acciaro, 2014	Wik and Niemi, 2016	Wu et al., 2018	Baresic et al., 2018

1.3 Using LNG as fuel for ocean-going ships

As compared with short sea shipping ships working within the ECAs, the barriers in capital investment cost and LNG bunkering are considered more challenging for applying LNG fuel to ocean-going ships beyond LNG carriers. Complexities of powering ocean-going ships with LNG fuel mainly lie in the changes in design, working mode, bunkering method, and location. However, there is still today a lack of studies that provide detailed analysis focusing on the economic efficiency of using LNG as fuel for general ocean-going commercial ships, despite the fact that this is the information that shipowners and involved stockholders want to know the most. This section analyzes the resistances and challenges of using LNG as fuel for ocean-going commercial ships. Such an analysis is not available in the literature, despite the idea of powering commercial ships with LNG fuel receiving wide attention from researchers, as reviewed above.

In the shipping sector, the resistance to using LNG as fuel for ocean-going general commercial ships is mainly related to the concerns of:

1) high capital expenses required;

2) the increasing space required by the LNG storage system;

3) lack of port infrastructure for LNG bunkering;

4) the LNG bunker price varying between different ports, affected by the LNG price in the local market, the bunkering methods used by the ports, and the total demand for the LNG bunker service in ports;

5) seafarers working onboard LNG-fueled ships being required to have additional training in order to allow them to properly and safely manage the LNG fuel and the LNG-related systems, which could lead to additional costs, and

6) switching to using LNG as fuel potentially requiring ships to use newly-formulated lubricating oil, stores, and spares. The lack of supply in the industry could lead to a higher price of these additives and spares.

The higher capital investment costs required are one of the main disadvantages of LNG-fueled commercial ships. The cost drivers of additional required capital expenses for all general LNG-fueled ships are mainly from the gas-related propulsion plant, fuel containment system, and associated technology and services (Wärtsilä, 2015). For ocean-going ships, lack of appropriate LNG infrastructure, such as bunkering facilities and supply chain in the global range, has further increased the obstacles to capital investment. Ocean-going LNG-fueled ships today tend to refuel in one or 2 specific ports, due to the shortage of LNG bunkering infrastructure. Therefore, in the existing designs, ocean-going LNG-fueled ships are generally designed to carry a larger volume fuel containment system which allows the ships to finish entire trips, or at least a half round trip. In the current design, the LNG containment system used by ocean-going ships is of a size of up to around 20,000 m^2 to meet the fuel demand. Although the addition investment lead by the LNG tank is relevant to the type of LNG tank selected for the design, based on the LNG tank price information provided by previous studies, a noticeable increase will be found in the capital expenses, no matter which type of LNG tank has been selected. Also, the high space demand of LNG containment systems is assumed to consume TEU slots, and that may result in lost earnings, especially for container ships (Clausen et al., 2012).

Based on the review of the existing literature, fuel cost performance has been widely accepted as a key factor determinant for LNG technology adoption in the shipping sector. The study of Baresic et al. (2018) and DMA (2012) are particularly noteworthy, which have critically evaluated the development of LNG bunkering infrastructure in the global range and assessed the prospective future LNG bunker price based on the supply chain of LNG fuel, bunkering method, bunkering infrastructure investment, and supply and demand of LNG fuel. In the studies, the LNG bunkering price will be determined by the LNG import price and the supply chain costs from the import terminal to the actual bunker location. From the user side, there are systematic, operational, and technical factors that hinder the wide use of LNG fuel in global shipping; the key challenges faced by ocean-going LNG-fueled ships are outlined:

First, ocean-going ships must carefully choose the bunkering point position to optimize the fuel cost. LNG prices in the global market today have strong regional differentiation. Yegorov (2009) explains that differences in gas prices can come from the gas itself, market influences, and the pricing mechanisms used by local markets. Today, the most common approach to consider the LNG bunker price in ports is the sum of the LNG hub price or import price in the local market and an adjustment for LNG bunkering. Therefore, for import countries, where the gas comes from and how it is transported to them are questions that directly influence the LNG import price and are further reflected in the local market's LNG bunkering price. Limited by fuel capacity, short seagoing LNG-fueled ships generally tend to bunker in ports near their working areas. However, for ocean-going LNG-fueled ships, the high fuel capacity allows them to freely choose the bunkering points on their routes. Considering fuel consumption, ocean-going LBG-fueled ships are more sensitive to fuel price changes than shore-based working LNG-fueled ships. Optimizing the bunkering point position may effectively help ocean-going LNG-fueled ships reduce their fuel costs.

Second, the LNG fuel distribution cost may higher for ocean-going LNG-fueled ships due to the bunkering method. In principle, there are currently 3 LNG bunkering methods available for port use, which are: Truck to Ship (TTS), Ship to Ship (STS), and Intermediate tank to ship transfer (TPS). The distribution cost for LNG fuel in port is mainly determined by the infrastructure cost (capital investment and operating cost) and burden in LNG bunker servicing. According to the existing literature, the infrastructure cost varies significantly from different bunkering methods. Algell et al. (2012) carried out a detailed analysis of LNG bunker changes, and several different LNG bunker examples were evaluated in their study. As the result, the study concluded that, under the various LNG supply chain and bunker methods, the additional supply cost of this fuel could vary from 50 US$/t of LNG up to 630 US$/t. In the following research, the investment costs of 15 to 137 million EUR were reported by Faber et al. (2015) for building LNG bunkering terminals in European ports. Different from shore-based working LNG-fueled ship, the re-fueling demand of ocean-going LNG-fueled ships can only be met by using LNG bunker ships or Intermediate tank. At the beginning stage of using LNG as a marine fuel, the higher infrastructure cost potentially leads to a more expensive fuel distribution charge for ocean-going LNG-fueled ships.

In addition to the challenges in capital investment and LNG bunkering discussed above, there are still more substantial uncertainties associated with using LNG as fuel for ocean-going ships, which include, but are not limited to, seafarer training, changes in maintenance processes and standards, and new lubricating requirements. All of these factors can be directly transferred to the variables that influence the lifetime costs of LNG-fueled ships. Thus, it is necessary to analyze the economic performance of LNG technology and assesses the commercial feasibility of using LNG as fuel for ocean-going general commercial ships.

1.4 Research objective and outlines

This paper is intended to answer fundamental questions in identifying the economic feasibility of using LNG as fuel for general ocean-going commercial ships. It, therefore, proposes a lifetime-based cost analysis approach aimed at providing a holistic view from an economic perspective of the strengths and limitations of using LNG as fuel for ocean-going ships in the long run; this will facilitate and support rational decisions by shipowners and relevant stakeholders about using LNG fuel on their ships.

To achieve this goal, Section 2 describes the general principles and process outlines of the cost evaluation framework and specifies the application of the approach into ocean-going LNG-fueled ships. A case study investigating the economic feasibility of using LNG as fuel for 3 varying sizes of LNG-fueled ocean-going container ships will be presented in Section 3 in order to demonstrate the application of the approach presented in the study. Key findings from the case study are discussed in Section 4. Finally, Section 5 will highlight and conclude the results in this paper.

2. Method

Life Cycle Cost Analysis (LCCA) is a technology that combines engineering and financial management and costing and is applied to take account of all the costs accrued during an asset's life cycle. One of the main objectives of the LCCA approach is to quantify the total costs generated during a product's life cycle (Onyemechi, 2016). The complexity of the conduct of an LCCA of a product means that wide-ranging techniques are used by this approach: for example, forecasting, cost-benefit analysis, preparation of cash flows, discounting, sensitivity analysis, cost estimating, probability theory, and so on (Okano, 2001). Through comparing the LCC result of alternative products and original products, buyers can easily understand the performance of alternative products in the economic aspect. In the shipping sector, the value of using an LCCA approach to analyze ships' economic efficiency has proven inestimable. Evaluating ships' costs from a lifetime perspective helps decision-makers to shift their interest from short-term gains from their ships to their lifetime benefits. The application of the LCC analysis approach in the shipping sector indicates a rising awareness at the design stage of the significance of understanding ships' LCC.

2.1 LCC performance analysis framework

In this study, the fundamental goal of LCCA is to establish a relative holistic evaluation of the LCC performance of LNG-fueled ocean-going ships. A novel LCCA approach is developed through combining the LCC, cash flow performance, and sensitivity and uncertainty analysis; this is called a Life-Cycle Costs and Cash Flow Performance Assessment (LCCFPA). **Figure 1** shows the procedure flows of the economic feasibility evaluation used in this study, where option means the available options for 2020 sulfur cap compliance, and i is the number of options.

For both retrofitting and for building new ships powered with LNG fuel, the economic feasibility of the project depends on the relative lifetime costs; therefore, the LCCA approach in this study is designed as a selective-design analysis. The economic efficiency of LNG-fueled ships is determined through comparing the LCC and the lifetime operating earnings, the net present value (NPV) and the payback period (PP) of selected LNG-fueled ships with equivalent baseline ships. LNG-fueled ships are recognized as 'alternative' cases, and conventionally-fueled ships with other sulfur limit compliance options are set as 'baseline' cases, with cost factors remaining the same for all cases.

In particular, the input factors which contribute to the baseline LCC in this study are denoted as $\vec{\delta} = (\delta_1, \delta_2, \delta_3 \dots \dots \delta_n)$, and the corresponding output LCC results of the baseline conventional case are represented by $\overrightarrow{C_\iota} = (C_1, C_2, C_3, \dots \dots C_n)$. Accordingly, the input factors in this study for LNG-fueled ships are denoted using $\vec{\theta}(\theta_1, \theta_2 \dots . \theta_n)$, and the relative changes to each baseline cost factor are identified as $\vec{\varepsilon}(\varepsilon_1, \varepsilon_2 \dots . . \varepsilon_n)$. The absolute output result from the LCC model is denoted by $\overrightarrow{C_\iota} = (C_1, C_2, C_3, \dots \dots C_n)$ **(Figure 2)**.

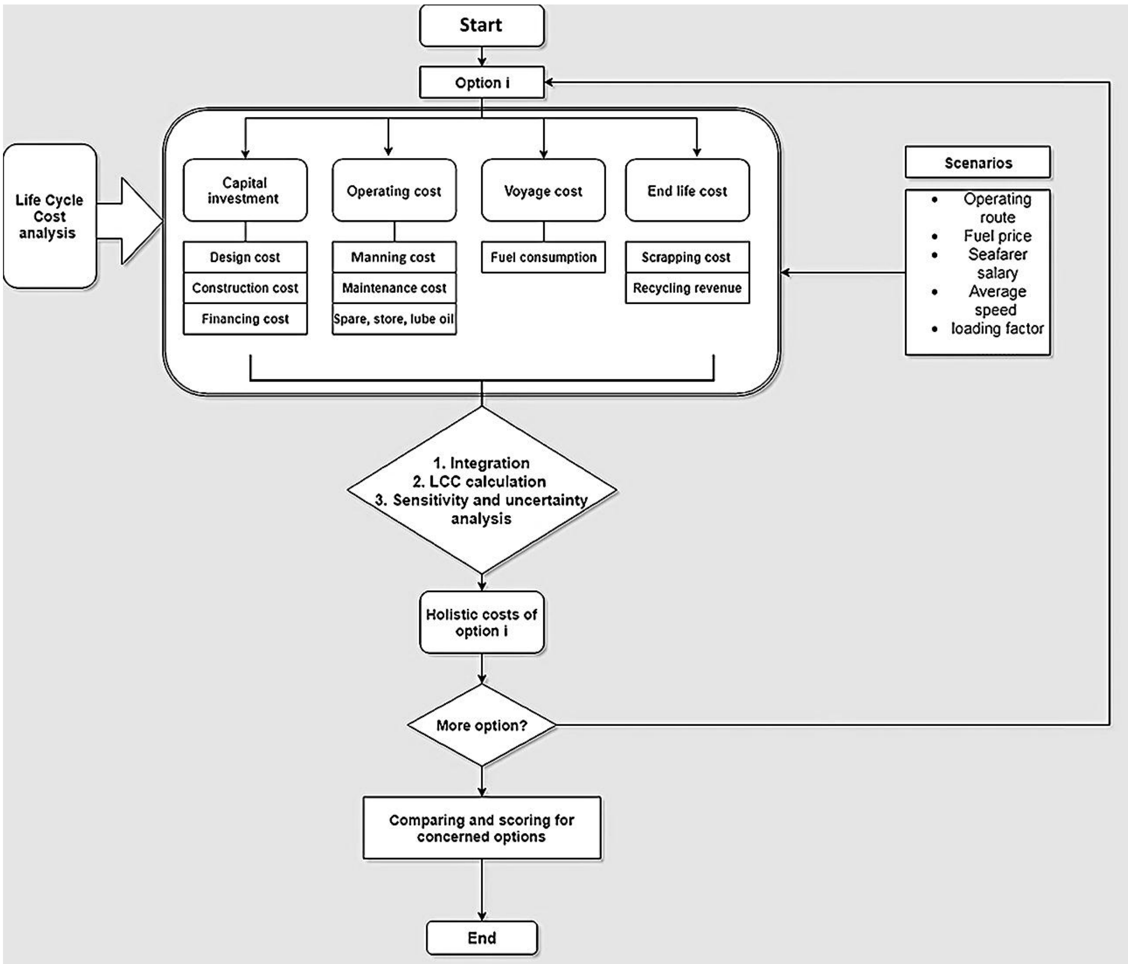

Figure 1 Procedure flow of the LCC analysis.

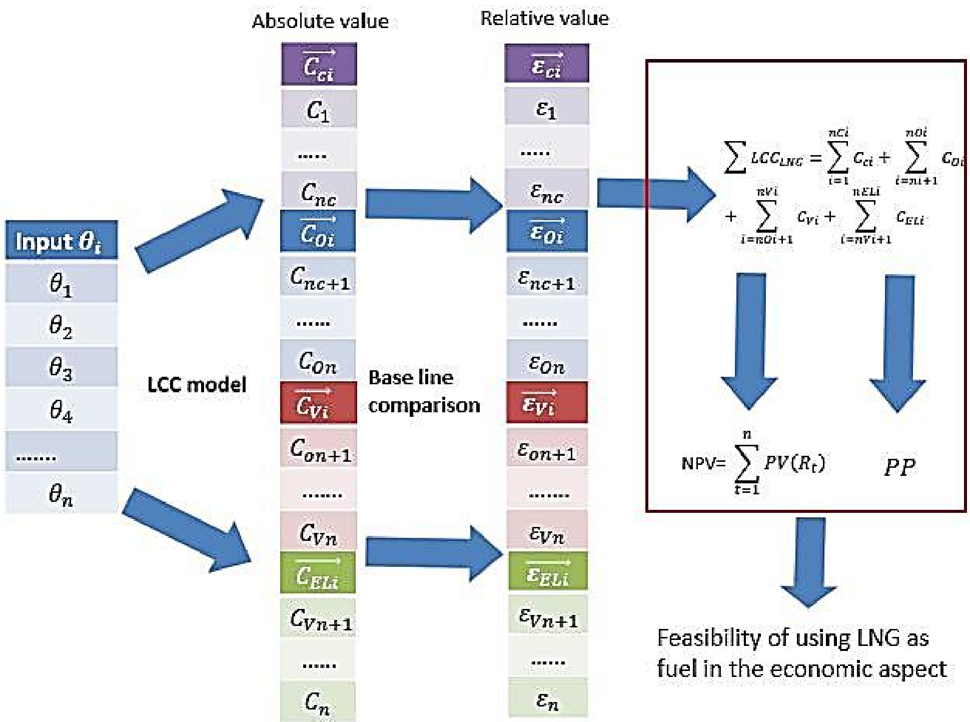

Figure 2 Process of LCC evaluation for LNG-fueled ships.

2.2 Formulation for LCC calculation process

The equations required to establish an LCCA model are presented in this section. The LCC of ships is calculated by the sum of the capital investment cost, operating cost, voyage cost, and end life cost, as shown in the formula:

$$\sum LCC_0 = \sum_{i=1}^{nCi} C_{ci} + \sum_{i=ni+1}^{nOi} C_{Oi} + \sum_{i=nOi+1}^{nVi} C_{Vi} + \sum_{i=nVi+1}^{nELi} C_{ELi} \quad (1)$$

where C_{ci} is the total capital investment costs of the ship in its lifetime;
C_{Oi} is the total operating costs of the ship in its lifetime;
C_{Vi} is the total voyage costs of the ship in its lifetime, and
C_{ELi} is the total end life costs of the ship in its lifetime.

The capital investment costs in this study are considered to consist mainly of design costs, ship construction costs, and other costs such as classification society service fees, technical support, and insurance fees, which are expressed as shown in Eq. (2):

$$C_{captial} = C_{Design} + C_{construction} + C_{Oter} \quad (2)$$

Ships' total construction cost in this study is here further broken down into costs of building the hull structure, the propulsion system, the electrical system, the navigation/communication system, the auxiliary system, outfit, the fuel storage system, and shipyard service fees. The construction cost $C_{construction}$ in this study is expressed as:

$$C_{construction} = C_{Hull} + C_{Popu} + C_{Elec} + C_{Nav/Comm} + C_{Auxi} + C_{Outfit} + C_{FS} + C_{SS} \quad (3)$$

The main differences in operating costs between LNG-fueled ships and conventionally-fueled ones at present are considered to come mainly from the factors of manning costs, maintenance costs, and the costs of purchasing lube oil, stores, and spares. The operating costs are estimated with the sum of the manning cost, maintenance cost, and cost for purchase consumables and lubricant oil, which can be expressed as:

$$C_{Operating} = C_{Manning} + C_{mainteance} + C_{lube} \quad (4)$$

The economic benefit of switching to LNG fuel is presently believed to come mainly from lower fuel costs. The fuel costs in this study are calculated using Eq. (5), which shows that the fuel costs of an operational ship are affected mainly by total working hours, unit fuel price, and fuel consumption:

$$C_{fuel} = \sum_{i=1}^{i} f_{pi} * t * daily\ fuel\ consmption \quad (5)$$

where t is the total working days of the ship in the year i, and
f_{pi} is the fuel price in the year i.

At present, the LNG bunkering price in port is the main interest of shipowners and operators in the industry. If we ignore the market forces in the marine fuel market, the bunker price of LNG fuel comprises 2 main components. As illustrated in the above formula, the prices that marine operators will pay for bunkering LNG fuel are the summed downstream LNG prices, with an adjustment for bunkering.

Cost of small-scale LNG = LNG end-user price in local port + Cost of distribution LNG fuel to vessel (6)

The end-life cost of the ships in this study is considered to be composed mainly of the c_8 revenues for scrap. In the shipping industry, when a ship's age limit has arrived, it is commonly sold to ship-breakers under a negotiated price per lightweight ton. The revenues for scrap can be expressed as:

$$C_{Scrap} = -k_{acrap} * \Delta_{ltw} \tag{7}$$

where k_{acrap} is the negotiated unit scrap price (USD/lwt), and
Δ_{ltw} is the lightweight tonnage of the ship.

The economic performance of LNG-fueled vessels is assessed by looking at the LCC, net present value (NPV) of LNG-fueled ships, compared with those of an equivalent baseline case. Vessels with higher NPV at the end of life are considered to have better lifetime cash flow performance. All LCC cost data in this study will be summed together and converted into 'invest NPV' data. By doing this, it is easy to compare the economic performance of LNG-fueled vessels and their equivalent baseline conventionally-fueled ones under the conditions specified here. The standard NPV approach is illustrated in Eq. (8):

$$\mathrm{NPV} = \sum_{i=1}^{n} PV(R_t) \tag{8}$$

where NPV is the present value of LCC;
R_t is the operating earnings of the ship in the period t;
r is the discount rate, and
t is the analyzed time.

3. Life Cycle Cost Assessment

The structure of LCCA analysis was presented and described in Section 2. This section provides a detailed case study in which to firstly demonstrate the application of the framework developed in this study in a practical setting, and secondly display the experiments aimed at numerically validating the lifetime-based cost evaluate approach and deriving generic insights on the benefits and challenges of using LNG as a marine fuel for ocean-going ships.

The whole LCC of ships has been split into capital investment costs, operating costs, voyage costs, and disposal costs. The key costs factors related to the LCC analysis in this study are established and are given in **Table 4**.

Table 4 Key cost factors related to LCC.

Life cycle stage	$\vec{C}$	**Cost-related factors**
Capital investment costs	c_1	Design costs
	c_2	Ship construction costs
	c_3	Other costs related to capital investment
Operating costs	c_4	Manning costs
	c_5	Maintenance costs
	c_6	Lube oil, stores and spares
	c_7	Other costs in operation
Voyage costs	c_8	Fuel costs
End life cost	c_9	Revenues from scrap

3.1 Case description

The costs and benefits of LNG as a marine fuel in the case study are presented in comparison to the baseline cases, which are assumed to comply with the 2020 sulfur limit with 0.5 % Low Sulfur Content fuel oil (LSFO). Three different types of ocean-going container ship have been selected for the case study; these are Post-Panamax (8,560 TEU), New Panamax (13,500 TEU) and Ultra Large Container vessel (20,600 TEU). In the case study, 2 bunker port cases, Singapore and Rotterdam, have been selected in order to test the potential influence of bunker location on fuel cost.

All design and operating data of the baseline conventionally-fueled ships in the case study are real-ship data collected from the databases of shipping companies and classification societies. The main parameters of the LNG-fueled ships in this study, such as the length overall (LOA), beam, depth, and total power installed, are assumed to be the same as the equivalent baseline conventionally-fueled ships. The key parameters of the ships are given in **Tables 5 - 7**.

Table 5 8560 TEU post-Panamax conventional container vessel.

Max load capacity (TEU)	**8,650 TEU**
LOA	330.5 m
Beam	43.2 m
Depth	27.6 m
Design max speed	23 knots
Lightship weight	21,000 t
Powered installed	67,100 kW
Fuel tank capacity	8,000 m^3
Officer number onboard	11
Rating number onboard	11

Table 6 13,500 TEU baseline New Panamax container ship.

Max load capacity (TEU)	**13,500 TEU**
LOA	365.9 m
Beam	51.2 m
Depth	29.9 m
Design max speed	22.5 knots
Lightship weight	27,000 t
Engine type	MAN B&W 12K98ME7
Powered installed	67,100 kW
Fuel tank capacity	8,000 m^3
Officer number onboard	11
Rating number onboard	12

Table 7 20,600 baseline Ultra Large conventionally-fueled container ship.

Max load capacity (TEU)	**20,600 TEU**
LOA	396 m
Beam	59.6 m
Depth	32.8 m
Design max speed	23.3 knots
Lightship weight	31,000 t
Engine type	MAN B&W 11G95ME-C9.5
Powered installed	80,000 kW
Fuel tank capacity	8,500 m^3
Officer number onboard	11
Rating number onboard	12

The cargo space loss onboard LNG-fueled ships in this study is according to the relation given by the DNV-GL's research (DNV-GL, 2015), when the LNG tank volume increases by 20 m^3, LNG-fueled container ships lose 1 TEU slot. The TEU slot loss of the 3 LNG-fueled ships are listed below.

Table 8 Cargo Capacity of LNG-fueled ships in this study.

	Group A LNG-fueled container ship	**Group B LNG-fueled container ship**	**Group C LNG-fueled container ship**
Tank Capacity (m^3)	13,800	13,800	15,600
Loss in cargo capacity (TEU)	690	690	780
Cargo capacity of ship (TEU)	7,870	12,810	19,820

3.2 Assumptions in the case study

At the time of conducting this study, LNG fuel has not yet been widely used by ocean-going ships. There are a number of optional conditions and options available for LNG fuel application, but they have yet to be practically decided by the ship-owners, fuel suppliers, and other relevant stakeholders. It is, therefore, necessary to make reasonable assumptions in order to help obtain reliable results in the LCCFPA. The assumptions in the working parameters in the case study are made on the basis of results from interviews with experts who work closely with LNG-fueled ships and LNG bunkering and from a review of the standard practices in the shipping industry. The assumptions made in this work are listed below:

a) the comparison between conventional-fueled and LNG-fueled ships should be based on the same energy required, market price, operating parameters, working time, and the average working speed.

b) All the container ships in this study are assumed to work between Shanghai port and Antwerp port via the Suez Canal. The round trip of the ships in this study is 22,000 NM, as shown in **Figure 3** below.

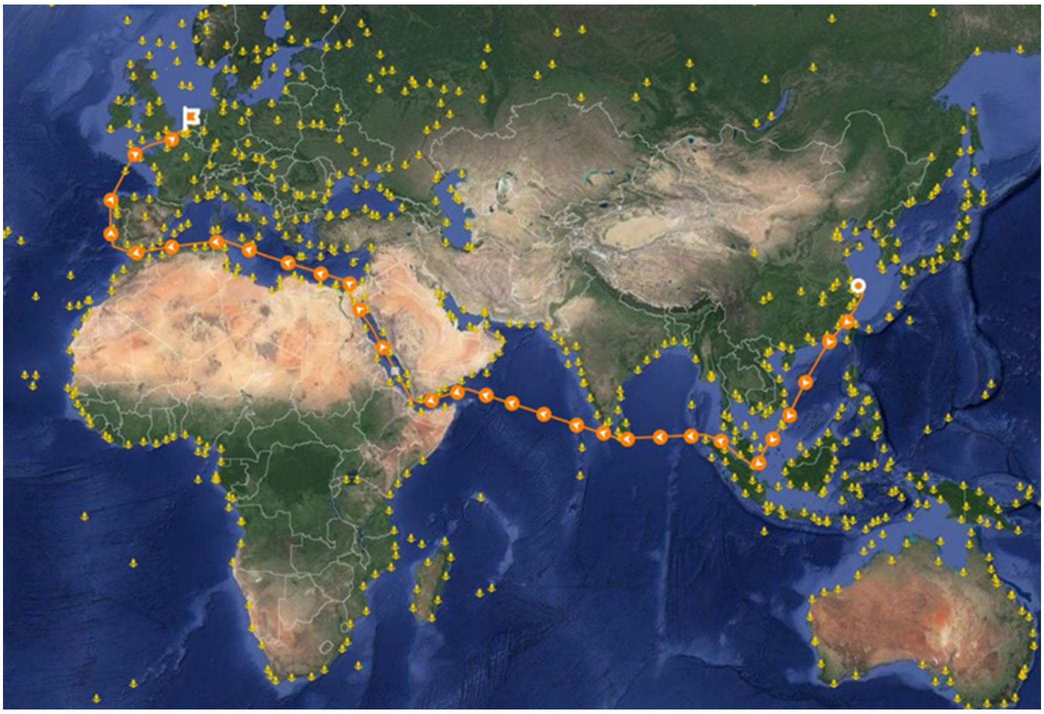

Figure 3 Operating route selected for ships in this study.

c) In this study, the assumed lifetime, t, for the ships tested in the LCC model is 25 years, with no further operation after their lifetime. When the lifetime service ends, the ships are assumed to directly proceed to the scrapping process.

d) The average working speed for the ships in the case study is 17 knots and, accordingly, the total time to finish a round trip is 80 days, with 55 at sea and 25 days in port. The ships in this study are assumed to finish 4 whole round trips in a year, with a total of 320 working days.

e) The structure design and the total power installed onboard the LNG-fueled ships is assumed to be exactly the same as the equivalent baseline conventionally-fueled ships.

f) The LNG-fueled ships are designed to carry an LNG fuel tank to allow the ships to finish the whole round trip under the design speed and without refueling.

g) The ships in this study are assumed to refueling in the ports of Singapore or Rotterdam using the spot fuel price. The influence of the long term fuel supply contract in bunker price is neglected in this study. For LNG fuel, the addition of bunker service fees charged by the fuel supplier is assumed to be 160 US$/ton using the STS bunker method, as based on the bunker cost projection from DMA (2012); Faber et al. (2015).

h) The amount of pilot fuel oil consumed by the LNG-fueled ships is assumed to be 2 % of energy consumed by the engine based on the data provided by the engine manufacture MAN B&W Engine.

i) All the ships in the case study are assumed to be directly funded and operated by the shipowners; the influence of the different chart types and financing methods on the capital investment costs and revenue is not included in this study.

j) The LCC performance of the LNG-fueled ships are determined by the relevant lifetime costs and cash flow; the study is focused only on the cost factors which are considered to have noticeable differences between the 2 type of ships. The rest of the cost factors are assumed to be exactly the same between the baseline and the alternative case. This is believed not to jeopardize the reliability of the result.

k) Seafarers working on board the LNG-fueled ships are assumed to be basically the same as the baseline conventionally-fueled ships. According to the advice of experts, an extra officer is added to the LNG-fueled ships, who are responsible for managing the LNG fuel onboard. The salary rate for this LNG fuel managing officer is assumed to be the same as for the second officer on board.

4. Result and discussion

This is one of the first studies to contribute significantly to understanding of the economic performance of using LNG as fuel for general ocean-going commercial ships through a critical and systematic LCCA and a case study. In considering the gaps identified, this study has discussed the economic feasibility of using LNG as a fuel for ocean-going ships and has explored, by means of its case study, the relationship between LCC and the key cost factors. The findings in the case study in this section are presented after examining the LCC using lifetime cash flow analysis, and sensitivity and uncertainty analysis. The estimates of the differences between LNG-fueled ships and conventionally-fueled ones in terms of their LCC, and the numerical results of the data analysis, are revealed in the following sections.

4.1 Results of LCC analysis

The results of LCC analysis of the 3 container ships are given in **Figure 4** and **Tables 10** and **11**, which indicate overall that using this as fuel has great potential in reducing the lifetime costs of ocean-going ships. Even though, because it is considered standard practice in the current container shipping industry, the ships in the case study are assumed to be working in fuel-efficient low-speed mode (which may greatly cut the economic benefit to be gained from using LNG fuel), the total cost saving from using LNG as fuel is still up to US$33,000,000. However, it must also be emphasized that, under the current LNG pricing system, the LCC performance of LNG fuel could vary significantly between different bunker regions.

The increases in LCC of LNG-fueled container ships in the case study are reflected mainly in the construction costs of the ships. In both cases evaluated in this study, a noticeable increase in the required capital investment cost can be found in all 3 LNG-fueled ‘alternative’ cases. As shown in **Table 8**, the increase in the capital investment costs for the LNG-fueled ships in the case study is between US$25,615,150 and US$36,813,700. Compared with the ‘baseline’ conventionally-fueled cases, the increase in the capital investment costs of the LNG-fueled ships in Groups A, B, and C, are 31.9, 27.3, and 27.9 %, respectively. The differences in capital investment cost between the 2 types of ship arise mainly from their energy systems; in particular, the fuel storage system, the engine system, the bunker station, the pipe system, and the generator sets. From the viewpoint of price, given the lack of supply and the special material required, there is a noticeable price difference between LNG-fueled energy-related systems and conventional oil-fueled energy-related systems.

Table 9 Overview of capital investment cost of ships in this study.

Group	Capital investment for LNG (US$)	Capital investment costs for baseline (US$)	Total additional costs for LNG installation	Unit costs for LNG installation (US$/kW)	Unit costs for LNG installation (US$/TEU)
Group A	114120150	88505000	25615150	421.3	2992.4
Group B	138802280	108997700	29804580	444.2	2207.7
Group C	168797800	131984100	36813700	460.2	1787.1

The economic advantage in the case study of using LNG as a fuel comes mainly from lower fuel cost. In some cases, the benefit reaped in fuel cost not only offsets the increase in capital investment cost, but also helps ships to have a lower total cost over their lifetime. A positive relationship has been recognized between fuel cost saving and LNG fuel consumption; this makes using LNG as fuel an ideal solution for a ship with high fuel consumption, such as a container ship. One should notice from the fuel cost results that this cost for LNG-fueled ships in the case study varied significantly between the different refueling cases. As was discussed in Section 1.2, the one noticeable difference between LNG fuel and conventional fuel oil is that the LNG bunkering price varies between different ports, because of the uneven distribution of natural gas resources and the different natural gas pricing mechanisms employed by local markets. With these differences in mind, the fuel costs of LNG-fueled ships in the case study were tested under 2 different bunkering scenarios; one was fueling in the port of Rotterdam (with a low LNG bunkering price), and the other was refueling in the port of Singapore (with a high LNG bunkering price). The results showed that the lifetime fuel costs obviously favored the LNG-fueled ships that refueled in the port with low LNG bunker price. The fuel costs saving of LNG-fueled ships in the Rotterdam refueling case was between US$55,016,938 and US$71,005,356. In contrast, there was no clear advantage for LNG-fueled ships in terms of fuel costs to be found in the Singapore cases.

Table 10 NPV results of Rotterdam refueling cases.

	Group A LNG-fueled ship	**Group A Baseline ship**	**Group B LNG-fueled ship**	**Group B Baseline ship**	**Group C LNG-fueled ship**	**Group C Baseline ship**
Lifetime	25	25	25	25	25	25
Discount rate	2.5 %	2.5 %	2.5 %	2.5 %	2.5 %	2.5 %
Inflation rate	4 %	4 %	4 %	4 %	4 %	4 %
NPV	273851194.9	322049735.2	655690178.4	704989005.6	1182679463	1239510372

Table 11 NPV results of Singapore refueling cases.

	Group A LNG-fueled ship	**Group A Baseline ship**	**Group B LNG-fueled ship**	**Group B Baseline ship**	**Group C LNG-fueled ship**	**Group C Baseline ship**
Lifetime	25	25	25	25	25	25
Discount rate	2.5 %	2.5 %	2.5 %	2.5 %	2.5 %	2.5 %
Inflation rate	4 %	4 %	4 %	4 %	4 %	4 %
NPV	213784840	299350486.2	589593383.6	679882021.7	1104680484	1210034643

As shown in **Figure 4**, from the LCC perspective, large-size container ships are considered more cost-efficient than smaller-size LNG-fueled container ships. From the perspective of capital investment cost, the TEU-based unit additional capital investment cost indicated that the unit capital investment cost of a mega-size container ship is noticeably lower than for the other 2 types of container ships. The unit additional costs add on for Group C mega-size container ships are only US$1,787/TEU, and for the other 2 types of LNG-fueled container ship, they are US$2,207.70/TEU and US$2,992.40/TEU. For the operation-related costs, no obvious increase has been identified in manning costs, maintenance costs, and other operating-related costs of the mega-size LNG-fueled container ship in the Ultra Large Container ship case. This could explain why, when building LNG-fueled ocean-going container ships, shipowners currently prefer ships larger than 15,000 TEU.

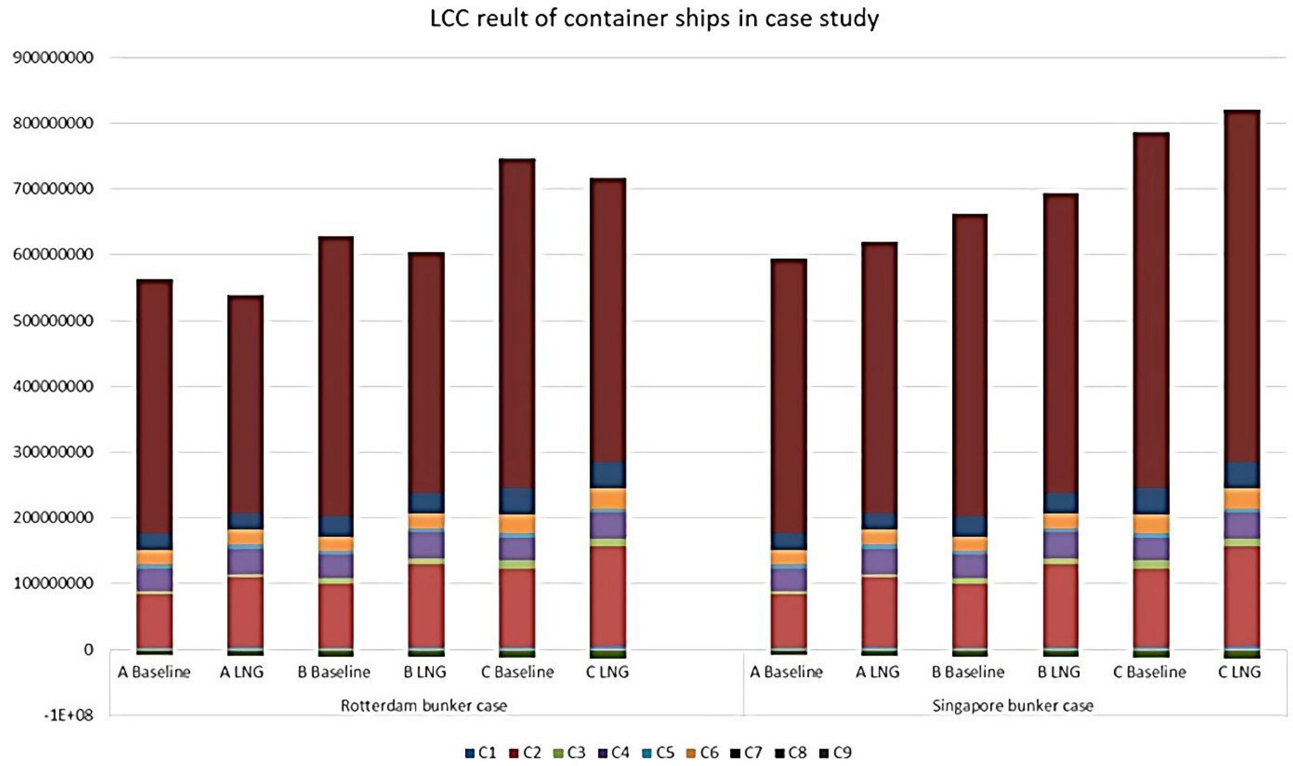

Figure 4 Overall LCC results of LCC model.

4.3 Sensitivity analysis

The sensitivity analysis in this study aims to assess the impact of the cost factors in the LCC of ships and further identify the costs factors which are considered have a high contribution to the LCC result. For each case, in total, 11 input factors are tested in the sensitivity analysis; the input factors are in this study are denoted by $\overrightarrow{f_k}(f_1, f_2 \dots \dots f_{11})$ and the respective model output life cycle costs under different changed cost factors f_k are denoted as LCC_k.

The input factors $f_k$in the analysis are varied one at a time, according to the given change rate X. The input t factors f_k in this study are calculated according to Eq. (8):

$$f_{kx} = f_{k0} \times (1 + x) \tag{8}$$

Among all the input factors tested in the sensitivity analysis, the 3 most important input factors in the LNG-fueled cases are f_{10} (Fuel price), f_5 (Average daily crew wage), and f_2 (Unit price of the population system). The input factor f_{10} (Fuel price) is more significantly important than the other cost factors. Even though, influenced by the low fuel consumption, the total voyage costs in the LNG-fueled cases are lower than the conventionally-fueled cases, the influence of the input factor f_{10} (Fuel price) is still around ten times higher than the second most important input factor. The up and down fuel price in the market brings significant uncertainty to the economic performance of LNG-fueled ships. However, it is almost impossible to provide an accurate projection for future fuel price in the long term. The uncertainty in the fuel cost will be evaluated using the Monte Carlo method to provide a deeper understanding of the economic efficiency and risks to the shipowners of using LNG as fuel.

Table 12 Input cost factors in sensitivity analysis.

	Input cost factors
f_1	Design costs
f_2	The unit price of the population system
f_3	The unit price of the electrical system
f_4	The unit price of the fuel storage system
f_5	Daily crew wages
f_6	Average annual maintenance costs
f_7	Average annual store purchase costs
f_8	Average annual spare purchase costs
f_9	Average annual lubricating oil purchase costs
f_{10}	Fuel price
f_{11}	Unit scrap costs

4.4 Uncertainty analysis in fuel cost

The input parameters in the uncertainty analysis are described by their 1) minimum value, 2) maximum value, and 3) most likely value. The input factor f_{10} (Fuel price) has been set following the standard normal distribution, with standard deviation σ = 1. The runs for the Monte Carlo simulation in the uncertainty analysis is set as n = 10,000 runs. The probability density function of the input factor f_{10} (Fuel price) in the uncertainty analysis can be presented as:

$$f\left(x_{fuel}\right) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x_{fuel}-\mu)^2}{2\sigma^2}} \tag{9}$$

where σ is the standard deviation, and
μ is the mean value of the fuel price.

The uncertainty analysis result is presented using the Cumulative Distribution Function (CDF), which is expressed as:

$$F\left(x_{fuel}, \sigma, \mu\right) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{x} exp\left(-\frac{(t-\mu)^2}{2\sigma^2}\right) dt = \frac{1}{2}\left[1 + \operatorname{erf}\left(\frac{x_{fuel}}{2}\right)\right] \tag{10}$$

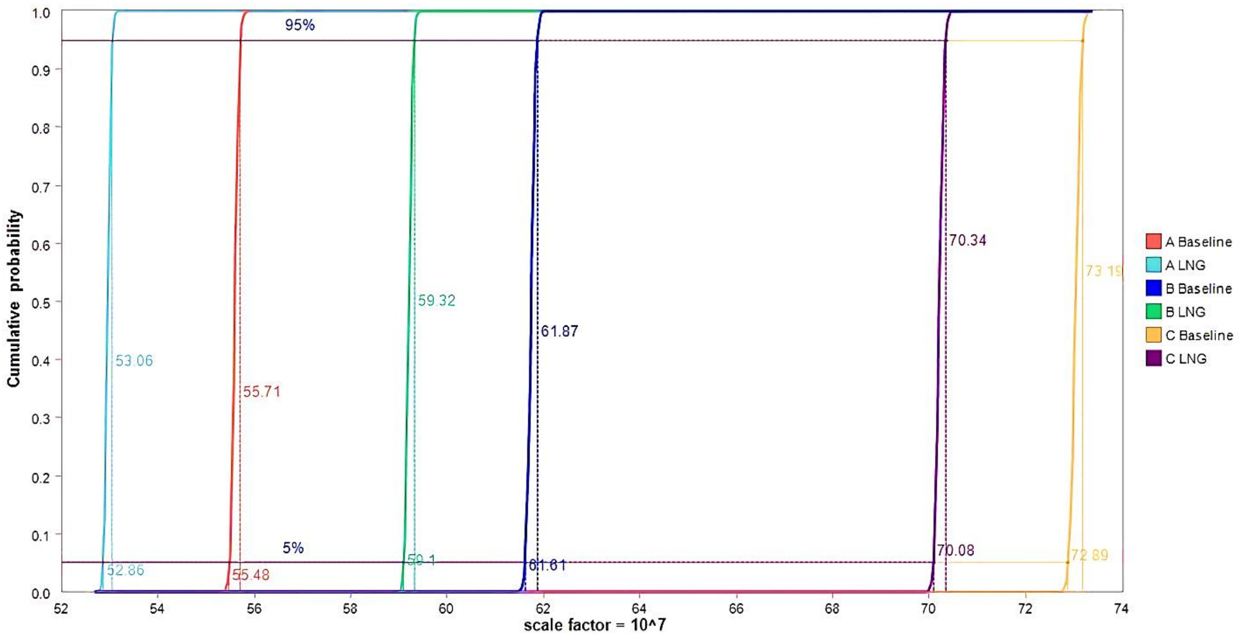

Figure 5 Cumulative distribution plot of LCC in Rotterdam bunker case.

The uncertainty analysis results presented in **Figures 4** and **5** indicate that the distribution of the Monte Carlo simulation results in both cases follow the symmetrical normal distribution, which marks the LCC result as being significantly influenced by the input factor. The uncertainty result is also favorable for low LNG bunker price cases. In the Rotterdam bunker case, LNG-fueled ships in all 3 cases have a high possibility of having lower LCC than the conventional 'baseline' cases.

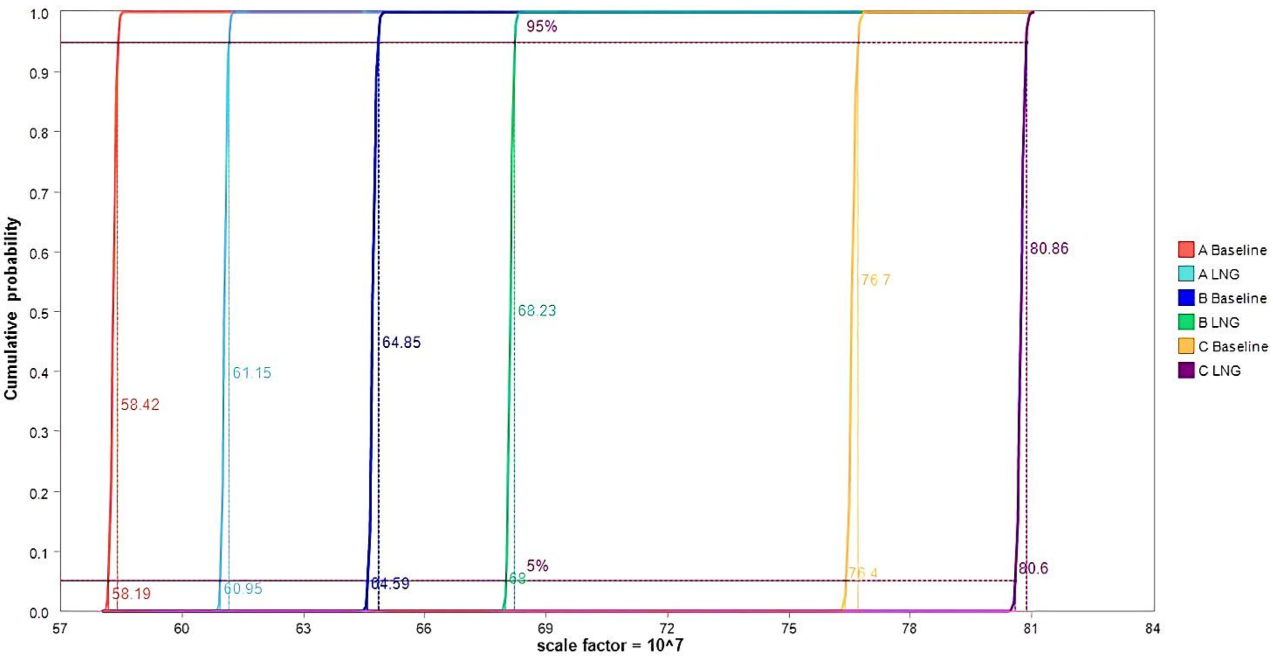

Figure 6 Cumulative distribution plot of LCC in Singapore bunker case.

5. Conclusions

In conclusion, this study has presented a detailed analysis that took a long-term perspective regarding the economic performance, the feasibility, and the commercial uncertainty about using LNG as fuel for ocean-going container ships. The analysis has filled gaps identified in the existing research about the benefits and disadvantages of using LNG as fuel for general ocean-going commercial ships. A lifetime-based cost analysis approach has been presented that allows stakeholders to compare economic-based performance between LNG-fueled ships and conventional oil-fueled ones.

Based on the quantitative economic performance analysis of the LCC, the lifetime cash flow, and the uncertainties in using LNG as a marine fuel, it is clear that: considering the differences in the LCC and cash flow performances between LNG-fueled ships and conventional oil-fueled ones found in the low-LNG-price bunker cases, the acquisition premium for ocean-going LNG-fueled container ships is sufficient to warrant the discount in terms of the LCC. This makes using LNG as fuel for ocean-going container ships economically feasible. However, based on current market conditions, even in the best case, the benefits in terms of the LCC may not seem adequate to convince shipowners and other stakeholders to invest in building or purchasing ocean-going LNG-fueled container ships; the drawbacks with respect to cash flow performance and the risks and uncertainties about operations and regulations require them to consider the issue further. In addition to economic performance, shipowners in the industry who are today ordering ocean-going LNG-fueled ships are also focusing on the potential of LNG fuel in emission reduction, fulfilling social responsibility and encouraging the development of an LNG bunker infrastructure.

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