Wan, C, Yan, X, Zhang, D and Yang, Z

A novel policy making aid model for the development of LNG fuelled ships

Wan, C, Yan, X, Zhang, D and Yang, Z (2018) A novel policy making aid model for the development of LNG fuelled ships. Transportation Research Part A: Policy and Practice, 119. pp. 29-44. ISSN 0965-8564

A Novel Policy Making Aid Model for the Development of LNG Fuelled Ships

Chengpeng Wan
(1) School of Energy & Power Engineering, Wuhan University of Technology
(2) National Engineering Research Center for Water Transport Safety, Wuhan University of Technology
(3) Department of Maritime and Mechanical Engineering, Liverpool John Moores University
Email: cpwan@whut.edu.cn

Xinping Yan
(1) School of Energy & Power Engineering, Wuhan University of Technology
(2) National Engineering Research Center for Water Transport Safety, Wuhan University of Technology
(3) Intelligent Transportation System Center, Wuhan University of Technology
Email: xpyan@whut.edu.cn

Di Zhang, Corresponding author
(1) National Engineering Research Center for Water Transport Safety, Wuhan University of Technology
(2) Intelligent Transportation System Center, Wuhan University of Technology
Email: zhangdi@whut.edu.cn
Y125 mailbox, No 1040 Heping Road, Wuhan University of Technology, Wuhan, Hubei 430063, P. R. China

Zaili Yang
(1) Department of Maritime and Mechanical Engineering, Liverpool John Moores University
(2) Shipping Management College, Dalian Maritime University
Email: z.yang@ljmu.ac.uk

Abstract

In recent years, increasingly strict restrictions on ship emissions and continuously increasing prices of marine fuel oil have made the liquefied natural gas (LNG) using as a marine fuel more attractive, and LNG fuelled ships have therefore become more popular in many countries. However, there is still not much research on the development level of LNG fuelled ships in different countries, and there is no unified or corresponding evaluation criteria established to support relevant policy making, revealing a significant research gap to be fulfilled. In view of this, taking the advantages of the PEST (Political, Economic, Social and Technological factors) and the SWOT (strengths, weaknesses, opportunities, and threats) analysis, this paper proposes a novel SRETI (Strategy, Regulation, Economics, Technology and Infrastructure) model for evaluating the development level of LNG fuelled ships in a particular region or country for self-assessment or comparative studies. The kernel of the model consists of the combination of the analytic hierarchy process (AHP) method and the evidential reasoning (ER) approach, thus being able to deal with evaluation data of both quantitative and qualitative features. China, Norway and the United States of America (USA) are selected in a real case study to demonstrate the feasibility of the model on the evaluation of the development of their LNG fuelled ships. The findings show that Norway is better than USA and China in terms of the development level of LNG fuelled ships. It is also revealed that the proposed SRETI model is capable of addressing uncertainties in subjective data provided by domain experts. A sensitive analysis is conducted as well to test the robustness of the SRETI model, and the results are in harmony with the axioms and hypotheses. This work provides policy makers with powerful insights for the development of LNG fuelled ships. It can also be tailored to evaluate the development of emerging technologies in other sectors.

Keywords: LNG fuelled ships, maritime transport, ship emissions, evidential reasoning approach, MCDM

1. Introduction

While shipping, carrying over 80% (in volume) international cargoes (Altunbulak, 2009), enjoys its cheap costs in international transport and trade, it renders serious environmental pollution due to air emissions (e.g. CO_2, SO_x and NO_x) (Jiang, 2009) caused by the use of traditional marine fuels. According to the International Maritime Organization (IMO), international shipping was responsible for about 2.7% of the global CO_2 emission in 2007 (IMO, 2009), and the percentage was expected to grow along with the development of the shipping industry. Therefore, a series of emission control measures have been developed over the past years to mitigate its severe negative environmental impact (Lv, 2009). During the 58th session held by the Marine Environment Protection Committee (MEPC), amendments were adopted to the International Convention for the Prevention of Pollution from Ships (MARPOL) Annex I, further restricting the emissions of air pollutants from ships. Consequently, shipping companies have to make necessary changes in order to meet stringent provisions, especially in Emission Control Areas (ECA). Among various existing choices for shipping companies, the use of the liquefied natural gas (LNG) as the bunker fuel is regarded as an effective option in terms of shipping safety, economy and emissions reduction.

Compared to other conventional fossil fuels, LNG has a series of superiorities including being non-toxic, non-corrosive and odourless (Kumar et al., 2011a). The abundant reserves as well as relatively low prices of LNG make it very competitive in international energy market. Thus, using LNG as an alternative to replace the marine fuel on-board ships is drawing growing attention from stakeholders (Kumar et al., 2011b). However, there are not many studies on evaluation of LNG as an alternative marine fuel on-board ship (Wan et al., 2015). The current literature on the application of the LNG in the transportation industry mainly focuses on generic LNG powered vehicles (Ma et al., 2013), or some specific technical issues around, for example, LNG leakages (Fu et al., 2016), LNG storage tanks (Shin et al., 2008) and LNG engines (Zhai et al., 2014). Despite the success in practice, the application of LNG to power ships is at large dominated by few developed countries (e.g. Norway), leaving the others (e.g. China) of owning large shipping fleets, who have the strong intention of developing LNG fuelled ships, to assess their shortcomings and develop effective measures in urgency. Besides, the existing studies on the development of the LNG as a marine fuel are carried out mostly based on the descriptive and qualitative methods, lacking of quantitative evaluation approaches and sound evaluation criteria. Therefore, this paper aims at developing a novel assessment model to evaluate the development levels of LNG fuelled ships on the basis of multiple criteria, representing the most important concerns of the stakeholders in developing LNG fuelled ships. In this process, the analytical hierarchy process (AHP) is used to estimate the weights of the defined criteria, while the evidential reasoning approach is used to synthesise the evaluation input data against each criterion by experts' judgments. Finally, the utility values are introduced to quantify evaluation grades for prioritizing alternatives. The robustness of the model is verified through a sensitivity analysis. A comparative case study is conducted to compare the performance of China with the ones of USA and Norway to 1) demonstrate the proposed model and methods, and 2) investigate the shortcomings of China in terms of developing LNG fuelled ships, particularly from strategy and policy making perspectives. This study contributes to the quantitative evaluation of the development of the LNG as a marine fuel and provides policy makers with significant insights on the development of LNG ships in future.

The rest of the paper is organized as follows. Section 2 compares the development of LNG fuelled ships in China and European countries, and introduces the background information of methods used in this study. Section 3 elaborates the SRETI model with focus on its structure and components. A comparative case study is conducted in Section 4, along with the validation of the proposed model. Finally, this paper is summarised in Section 5.

2. Background Information

2.1 Comparison of development of LNG fuelled ships in China and other countries

According to the Det Norske Veritas (DNV, known as DNV GL after 2013), there were in total 59 LNG fuelled ships (not including LNG carriers and inland ships) in operation worldwide until March 2015, and 80 ships were on order (Global news, 2015). The majority of LNG fuelled ships are classified by the DNV GL, while the rest of them belong to other authorities such as the American Bureau of Shipping (ABS), Lloyds Register of Shipping (LR) and Korean Register of Shipping (KR), to name a few. Most of them are ferries, while other seagoing ships include platform supply vessels, patrol boats and tugs. In China, by the end of 2013, 121 ships (115 inland ships and 6 seagoing ships) had been approved by China Maritime Safety Administration (MSA) to conduct ship conversion, 107 of which are currently undergoing major modifications. Two main areas for the trials of the converted ships are Beijing-Hangzhou Grand Canal and the Yangtze River. Detailed information on the converted ships in China can be found in Table 1. It is clear that the main ship types are bulk carriers, dry cargo ships and port tugs. The majority of the converted ships are equipped with only one LNG storage tank with a maximum volume of 20 m^3, and almost all converted main engines are working in the mode of single point injection when supplying LNG fuel.

Table 1 Converted LNG fuelled ships in China

Built year	Ship name	Ship type	Deadweight	LNG storage tank's capacity	Engine Type*
2010	Tug #302	Tugboat	-	4*0.45 m^3	SPI
2010	Sushu cargo #1260	Bulk carrier	-	-	SPI
2011	Lijiang #34	Cruise ship	-	-	SPI
2011	Changxun #3	Bulk carrier	2660 t	2*3 m^3	SPI
2011	Hongri #166	Bulk carrier	2640 t	1*15 m^3	SPI
2011	Fuzhou #0608	Dry cargo ship	1585 t	1*5 m^3	SPI
2011	Luji cargo #2535	Bulk carrier	-	1*10 m^3	SPI
2012	Baoying #98	Bulk carrier	4600 t	1*15 m^3	SPI
2012	Changneng #12	Dry cargo ship	7295 t	1*20 m^3	SPI
2012	Wuhu #6	Bulk carrier	8300 t	1*15 m^3	SPI
2012	Silver Huaxi #678	Dry cargo ship	1864 t	1*15 m^3	SPI
2012	Jinbao#106	Dry cargo ship	7054 t	1*15 m^3	SPI
2012	Haixing#688	Dry cargo ship	1080 t	1*5 m^3	SPI
2012	Luji dredger #0099	Dredger	-	2*60 m^3	SPI
2013	Xiangyue #1332	Sand carrier	-	1*3.5 m^3	SPI
2013	Haichuan#3	Bulk carrier	-	1*15 m^3	SPI
2013	Tug	Harbor tugboat	-	2*25 m^3	-

* SPI means Single-point Injection

Source: Research project "Navigational safety evaluation and risk control measures of LNG fuelled ships" from China MSA and National Energy Administration of China.

To facilitate the development and application of LNG as a marine fuel in China, the Chinese maritime authorities, together with shipping companies, have carried out a series of studies on LNG fuelled ships, especially those in inland waterways. In a sub-topic of the national research project "Navigational safety evaluation and risk control measures of LNG fuelled ships" organised by China MSA and National Energy Administration of China, the development of LNG fuelled ships between China and European countries were compared from different aspects such as LNG power related techniques, development of infrastructure supporting the operation of LNG fuelled ships, relevant specifications and regulations, etc. The comparison work was conducted through the analysis of all kinds of information collected through different resources like archives, literature, regulations, news, and statistics. The results are summarised and shown in Table 2. In particular, LNG fuelled ships discussed in this paper refer to those using the LNG as the bunker fuel (in internal combustion engines) rather than LNG fuelled steamships (e.g. LNG carriers).

Table 2 Comparison of development of LNG fuelled ships between China and European countries

Attributes \ **Interpretation**		**European countries**	**China**
Techniques issues	**Engine type**	Newly built gas and dual fuel engines.	Mainly converted dual fuel engines.
	Heat exchanger	High-end products using modern technologies.	Less developed products with outdated design standards and techniques.
Infrastructures		Relatively mature in Norway. The EU is speeding up the construction of LNG filling stations.	In a developing period; lack of sound technical standards.
Specifications & Regulations		Research started earlier with strict requirements. But there is a lack of regulations specifically for the European inland waters and LNG filling process.	At the exploratory stage. Currently it has formed some relevant management and technical standards.
Current operation situation	**Ship type**	Mainly ferries, platform supply vessels, patrol boats, chemical tankers and tugs.	Mainly bulk carriers, dry cargo ships and port tugs.
	Sail area	Mainly in European countries like Norway and Netherlands, shipping along coastal routes, port to port.	Mainly in inland waterways like Beijing-Hangzhou Grand Canal and Yangtze River, with long distances.

2.2 Literature on the used methods

The LNG was first used on LNG carriers as early as the 1960s (Wang, 2013), but it had not been used on other types of ships as the main propulsion fuel until 2000 due to technical reasons of applicability and safety. Therefore, the current research is focused more on LNG carriers rather than other types of ships. At present, most studies have been conducted with the focus on the development process of LNG fuelled ships, operations of pilot ships, regulations and standards, safety, suitability and economics of the LNG, and difficulties of the development of LNG fuelled ships using qualitative analysis (Burel et al., 2013; Zhou et al, 2013; Blikom, 2012; Wang & Notteboom, 2013). Few studies have assessed the development level of LNG fuelled ships quantitatively (Parsons, 2012).

2.2.1 Situational analysis tools

The political, economic, social and technological (PEST) analysis as well as the strengths, weaknesses, opportunities and threats (SWOT) analysis are the two qualitative methods most commonly used in the analysis of both internal resources and external environment of an organization, aimed at proposing strategic decisions (Nordtun, 2012). These methods can help to conduct an overall analysis, and can also be applied to the evaluation of the development potential, status and trends in the market or industry.

2.2.1.1 PEST analysis

The PEST analysis is an effective tool used to check the external environment of organizations from a macroeconomic perspective. Since every industrial sector and enterprise has its own characteristics of development, the specific criteria used in the PEST analysis may vary. However, the political, economic, social and technological factors are four main aspects which need to be considered when assessing the external environment (Ha & Coghill, 2006).

2.2.1.2 SWOT analysis

The SWOT analysis is one of the most popular techniques used in the strategic science (Dyson, 2004). It provides a systematic analysis of case studies (Kajanus, et al., 2004). The SWOT has been extensively used in strategic decision-making and competitive analysis in many fields, such as the market research, business management and competitor analysis (Halla, 2007). When conducting the SWOT analysis, all internal factors, such as strengths and weaknesses, are usually gathered together, and then evaluated with external factors, such as opportunities and threats.

2.2.1.3 Limitations of above methods

The PEST method puts emphasis on the analysis of the macroeconomic environment, which usually results in the high complexity of selected indicators due to the diversity of the research object itself. It becomes even worse when more comprehensive and detailed results are required. At the same time, the SWOT analysis cannot evaluate the situation comprehensively and thus can lead to a weak correlation among various aspects (Guo & Yang, 2012). In addition, both approaches lack any quantitative measurement on the importance of each factor. Therefore, it would be difficult to determine the importance degree and express it in a numerical value precisely (Tahemejad et al., 2013). Generally, these methods are used in the development trend analysis, but they are not suitable for the comparison of development levels of industries and enterprises in different regions.

2.2.2 Multiple criteria decision making (MCDM) methods

2.2.2.1 Analytic Hierarchy Process method

The Analytic Hierarchy Process method (AHP) was developed by Saaty and it is designed to solve complex multi-criteria decision problems (Saaty, 1980). AHP requires the decision makers to supply judgments about the relative importance of each criterion and then specify a preference for each decision alternative using each criterion. AHP is especially appropriate for complex decisions which involve the comparison of decision criteria that are difficult to quantify. It is based on the assumption that when faced with a complex decision the natural human reaction is to cluster the decision criteria according to their common characteristics.

Since AHP was introduced more than three decades ago, it has found many useful applications due to its useful characteristics (Anderson et al., 2003), such as being able to handle situations in which the unique subjective judgments of the individual decision makers constitute an important part of the decision making process, and relative easiness handling multiple criteria. Thus, the AHP method is used in this study to calculate the relative weight of each index within each level through pairwise comparison among them.

2.2.2.2 Evidential reasoning approach

The evidential reasoning (ER) was developed in the 1990s to deal with MCDM problems under uncertainty. The ER algorithm is based on the decision theory and the D-S (Dempster-Shafer) theory of evidence, and it is well suited for handling of the incomplete assessment of uncertainty (Jiang et al., 2012). The algorithm can be used to aggregate criteria of a multilevel structure. The ER has been widely used in many applications such as the system safety, risk assessment, organizational self-assessment and supplier assessment (Yang, 2001; Chin et al, 2003).

3. Development of the SRETI Model

Based on the expert investigations and comprehensive analysis of the mainstream research on LNG fuelled ships in different countries, the SRETI model for the evaluation of the development of LNG fuelled ships is constructed in a hierarchical structure.

The SRETI model is composed of three levels and it is a set of evaluation indexes selected according to the characteristics of the global shipping industry related to LNG fuelled ships. The top level is called the goal level which is generally the object of this study. The second level is the criteria level, and it is composed of five aspects, namely, the strategy, regulation, economics, technology and infrastructure. Based on these criteria, different indexes can be generated. All the indexes which can be evaluated directly through statistics data or expert judgments make up the third level-the index level (sub-index levels may be added if required). Based on the following analysis, we establish a hierarchal model to evaluate development level of LNG fuelled ships. The structure and indexes of the SRETI model are shown as Figure 1, while their selection is justified and their meanings are provided below.

All the bottom indexes are determined according to relevant elements in their immediate parent levels. Therefore, the factors in the criteria level are of significance in generating suitable evaluation indexes. Strategies represent a series of planned actions from management authorities, or even governments, which will greatly affect the development trend of the targeted industry. Thus the supporting polices from the government are of great significance to achieve a stable and fast development process. In addition, the development of LNG fuelled ships is related not only to the shipping and shipbuilding industries, but also to the adjustment of the energy consumption structure of a country due to its requirement of the increasing utilization of the LNG as a marine fuel. Regulations regarding to the development of LNG fuelled ships are those official rules which can either motivate shipping companies to make changes, or guide them on ship design, construction, conversion, and daily operations. Both strategies and regulations mainly reflect the overall development trend and degree of support for the development of a certain industry from a country or region, reflecting the level of the “soft power” of industrial development. Publicly owned ships may be built not for a single purpose of making profit like the private ones. In practice, owners have less motivation gained from a commercial perspective to protect environment, particularly when the associated cost incurred results in the increase of freight rates. Therefore, economic issues play a crucial role in the analysis of the development of an emerging technique, which will ultimately determine the stakeholders’ decisions. Existing marine engines are not suitable for using LNG as fuel, leaving the two alternative options to be a conversion or instalment of LNG propulsion machinery in newly built ships in order to use it properly. However, both of them are associated with high capital expenditures (Heir et al, 2011), and cost related to the design and conversion of a LNG fuelled ship (or construction cost of a newly built one) usually leads to a very high initial investment for ship owners to consider, which hinders the widely applications of LNG as a marine fuel. Another type of cost is to train qualified crews to support the reliable and efficient operations of this type of ships. In addition, the maintenance cost will inevitably increase due to the newly added unites and/or systems, such as LNG tanks, gas valve unites, heat exchangers, and pressure control systems. Cost of the LNG fuelling/refuelling on-board ships is determined by various factors, including the CIF (cost, insurance, and freight) price of LNG, loading charge, transport charge, and LNG filling fee (Zhou et al., 2013). Technology is the backbone in the development of an industry which can promote increasing efficiency and reducing cost. In terms of the LNG fuelled ships, these related aspects need to be considered with priority in order to maintain the safety, efficiency and sustainability of daily operations and management of LNG fuelled ships. They are LNG storage and supply systems, machinery arrangement of engine room, monitoring, control and safety systems, LNG loading/unloading equipment, as well as key technologies of marine engines, such as design of different engine types (e.g. Diesel-LNG dual fuel engine, and gas engine), the electronic control technique, and the high pressure fuel supply technique. Infrastructure provides a basic environment for LNG transportation and distribution so that LNG fuelled ships can work properly. This criterion is further analysed from aspects related to the receiving, bunkering, storage, and production of LNG. LNG receiving terminals are points of arrival of the LNG carriers where the LNG is unloaded, stored, and then distributed to other places. LNG bunkering facilities refer to the means to fuel/refuel the LNG ships. Generally, bunkering tasks can be fulfilled through four ways, including LNG terminals, tanker trucks, tanker ships/barges, and land based storage tanks (Oskar, 2008). LNG is normally stored in the LNG storage tanks with pre-stressed concrete outer wall and a high-nickel steel inner tank (Wikipedia, 2016). Thus the number and quality of LNG storage tanks can be an index reflecting the development of LNG industry of a country. An LNG production plant is the place where nature gas is transformed into the LNG by liquefaction so that it can be transported to other countries worldwide through pipeline or LNG carriers. Technologies and infrastructure reflect the scientific and technological development, capital investments, construction status, etc. the combination of them represents the level of the “hardware” of industrial development.

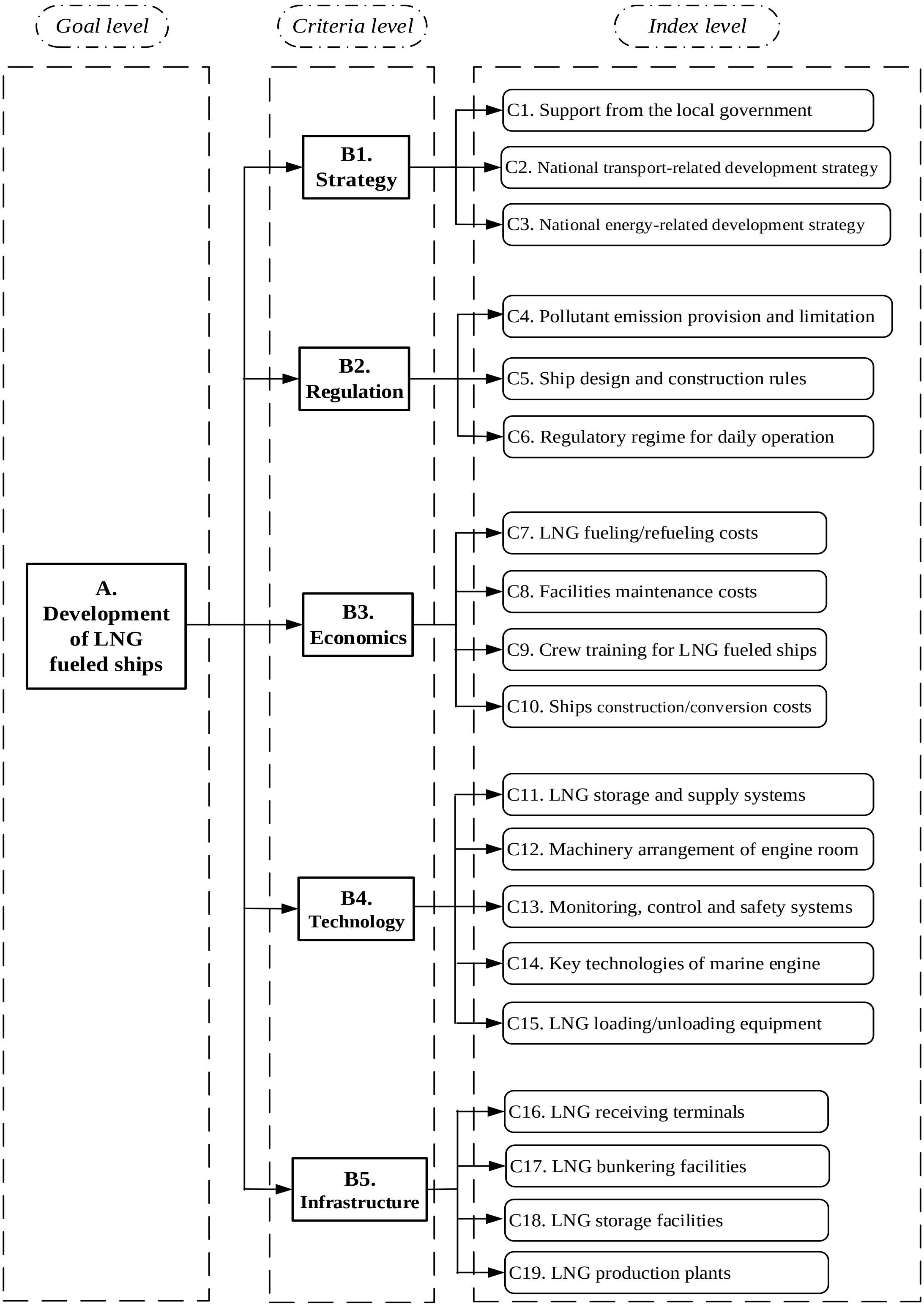


Figure 1 SRETI model for the evaluation of the development level of LNG fuelled ships

On the basis of the proposed SRETI model, this paper quantitatively evaluates the development statue of LNG fuelled ships in different countries, and uses the ER approach to integrate the judgments on the indexes of the bottom level to obtain a final evaluation result. Gaps of the development of LNG fuelled ships between China and other countries are analysed to aid policy makers for the development trend of LNG fuelled ships in China. Research steps are listed as follows.

Step 1. Calculation of the weight of each index in the SRETI model. The relative weight of each index within each level is determined through pairwise comparison and calculated through the AHP method, further explained as Table 3.

Table 3 The Relational scale for pairwise comparison (adapted from Saaty (1980))

Scale of importance	Interpretation
1	Equal importance
3	Weak importance of one over another
5	Essential importance
7	Very strong importance
9	Absolute importance
2, 4, 6, 8	Intermediate values between adjacent scale values

Based on a scale of relative importance (see Table 3), pairwise comparison can be conducted among criteria in each level of the SRETI model, and pairwise comparison matrixes can be construct accordingly. Then, the pairwise comparison matrix is converted into a single-value comparison matrix. The quantified judgements on pairs of criteria A_i and A_j are represented by a $n \times n$ single-value comparison matrix A:

$$A = a_{ij} = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ 1/a_{12} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/a_{1n} & 1/a_{2n} & \cdots & 1 \end{bmatrix} \quad (1)$$

where, a_{ij} is the relative importance of criteria A_i and A_j.

The weighting vector of a specific index k can be calculated through Eq. (2).

$$w_k = \frac{1}{n}\sum_{j=1}^{n}(a_{kj} / \sum_{i=1}^{n} a_{ij}) \quad (k = 1, 2, ..., n) \quad (2)$$

where, a_{ij} is the entry of row i and column j in a comparison matrix of order n and W_k is the weighting vector of a specific index k in the SRETI model.

The consistency of judgments is checked in order to guarantee a reasonable result. The comparisons will be considered reasonable only if the consistency ratio is equal to or less than 0.10 (Anderson et al, 2003). An approximation of the ratio can be obtained using the algorithm described in Eq. (3).

$$CR = \frac{CI}{RI} \quad (3)$$

Where, CR is the consistency ratio and RI (shown as Table 4) is the random index in terms of the matrix size. CI is the consistency index that can be obtained from Eq. (4).

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (4)$$

where, λ_{max} is the maximum weighting value of a $n \times n$ comparison matrix.

Table 4 Average random index (RI) values (Anderson et al, 2003)

Matrix Size (n)	2	3	4	5	6	7	8	9	10
RI	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Step 2. Definition of assessment grades. As most of the indexes in the SRETI model are qualitative with emphasis on the development of LNG fuelled ships from different aspects, where expert knowledge is usually needed to assist the judgement, linguistic variables can be very useful. In this study, five linguistic grades are used for evaluating these indexes, which are Best, Good, Average, Poor and Worst (Luce et al., 1997). The evaluation scales in terms of the five selected grades are defined for respondent's reference on conducting evaluation on those indexes.

Step 3. Evaluation based on the SRETI model. Experts' judgments are aggregated through ER approach to obtain a distribution of grades of each bottom index, and then integrated level by level in order to achieve the evaluation of the goal level.

Let Θ be a recognition framework, representing a set consisting of N possible results of the target object. A basic probability assignment on the Θ is represented by the function m ($2^{\Theta} \rightarrow [0, 1]$), which satisfies the rules 1) m ($\varnothing$) = 0 and 2) $\sum_{A \subseteq \Theta} m(A) = 1$, where $\varnothing$ represents the empty set, and A is any subset of the set Θ. Suppose two evidences m_1 and m_2 come from different sources of information, then the synthesis rules of these two evidences are as follows. In this study, each index is referred as evidence.

$$m_1 \oplus m_2(A) = \frac{1}{K} \sum_{B \cap C = A} m_1(B) \cdot m_2(C) \tag{5}$$

$$K = \sum_{B \cap C \neq \varnothing} m_1(B) \cdot m_2(C) \tag{6}$$

K is the normalizing factor. However, the conflict of evidences according to this algorithm may lead to unreasonable results. Several improved algorithms have been proposed to solve the problems of obtaining unreasonable results due to the evidence conflicts, among which one method is illustrated below, and applied in this study. Suppose the weights of indexes in the STREI model are W_1 and W_2, respectively, and $\{W_1, W_2\} \subseteq [0, 1]$, $W_1+W_2=1$. Then, the improved algorithm for index synthesis is as follows (Liu et al., 2008):

$$[m_1 \oplus m_2](X) = \tilde{m}_x \, / \sum_{X \subseteq \Theta} \tilde{m}_x \tag{7}$$

where,

$$\tilde{m}\ (X) = [(1-w_2)m_{X,1} + (1-w_1)m_{X,2}] + \sum_{B \cap C = A} m_{B,1} \cdot m_{C,2} \tag{8}$$

Step 4. Calculation of utility values. Grades are transformed into crisp values using the utility functions for the convenience of comparison of development level among different countries.

Suppose the utility of the evaluation grade H_n (five grades in this study are Best, Good, Average, Poor and Worst) is denoted by u (H_n) and u (H_{n+1}) > u (H_n) if H_{n+1} is more preferable than H_n (Yang & Xu, 2013). Then, the utility of the general criterion can be calculated using the linear distribution, Eq. (9) and (10):

$$u\left(H_n\right)=\frac{n-1}{N-1}\text{, n = 1, 2,…, N} \tag{9}$$

Where, N denotes the number of the linguist terms, which is 5 here, and

$$u\left(E\right)=\sum_{n=1}^{N}\beta_n u(H_n) \tag{10}$$

Step 5. Sensitive analysis. The sensitive analysis is conducted as a test and validation of the proposed model based on three well-established axioms and two hypotheses (see Section 4.5 for details) especially for the situation in this study.

When a new model is developed, a careful test is required to test its soundness. It is especially important and desirable when subjective elements are involved in the evaluation process based on the proposed model. In this study, a sensitivity analysis is conducted to test the development evaluation framework for LNG fuelled ships. In this study, sensitivity analysis in the proposed model with the ER approach refers to analysing how sensitive the outputs (the average utility values of development level in terms of different countries) are to minor changes in inputs. The changes may be variations of the parameters of the model or may be changes of the evaluation results (brief degrees assigned to the linguistic variables used to describe the parameters) of the parameters. If the proposed model with the ER approach (which is used to synthesise the evaluation results of the indexes of the model) is sound and logical, then the sensitivity analysis must at least follow the following three axioms (Yang et al., 2005).

Axiom 1. A slight increment/decrement in the degrees of belief associated with any assessment grades of the lowest level factors will certainly result in the effect of a relative increment/decrement in the average utility values of development levels of LNG fuelled ships.

Axiom 2. Given the same variation of belief degree distributions of the lowest level factors, its influence magnitude to the average utility values of development levels of LNG fuelled ships will keep consistency with their weight distributions.

Axiom 3. The total influence magnitudes of *x* factors (evidence) in the lowest level on the average utility values of development levels will be always greater than the one from the set of *x*-*y* ($y \in x$) factors (sub-evidence).

4. Case Study

4.1 Calculation of the weights of indexes

China, Norway, and the USA are investigated in the case study to compare their development levels in terms of LNG fuelled ships. The data used for the calculation of the weight of each index is obtained based on an interview of three experienced domain experts, and their details are shown below:

- Expert No.1: A captain working on-board LNG fuelled ships for more than 8 years.
- Expert No.2: A professor engaged in maritime economics research for more than 8 years.
- Expert No.3: A senior officer engaged in the management of maritime environment for more than 10 years.

Pairwise comparisons among the identified indexes are carried out by the three domain experts, respectively. Considering their working experience, these experts are given the similar weights (0.3, 0.3, and 0.4.) when merging their judgments. Based on the AHP method, altogether six pairwise comparison matrixes in terms of the criteria and index level can be established through Eq. (1), and the weight of each index can be calculated using Eq. (2). The results are summarised in Table 5.

Table 5 Weight of each index in the SRETI model

Criteria level indexes	weight	Indexes in the index level	Local weight	Global weight
B1. Strategy	0.2	C1. Support from the local government	0.46	0.092
		C2. National transport-related development strategy	0.32	0.064
		C3. National energy-related development strategy	0.22	0.044
B2. Regulation	0.2	C4. Pollutant emission provision and limitation	0.4	0.08
		C5. Ship design and construction rules	0.32	0.064
		C6. Regulatory regime for daily operations	0.28	0.056
B3. Economics	0.2	C7. LNG fuelling/refuelling costs	0.28	0.056
		C8. Facilities maintenance costs	0.22	0.044
		C9. Crew training for LNG fuelled ships	0.18	0.036
		C10. Ships construction/conversion costs	0.32	0.064
B4. Technology	0.2	C11. LNG storage and supply systems	0.2	0.04
		C12. Machinery arrangement of engine room	0.16	0.032
		C13. Monitoring, control and safety systems	0.24	0.048
		C14. Key technologies of marine engine	0.3	0.06
		C15. LNG loading/unloading equipment	0.1	0.02
B5. Infrastructure	0.2	C16. LNG receiving terminals	0.18	0.036
		C17. LNG bunkering facilities	0.42	0.084
		C18. LNG storage facilities	0.28	0.056
		C19. LNG production plants	0.12	0.024

4.2 Definition of assessment grades

Evaluation scales are important as they set a unified baseline for respondents when making their judgements. In this study, evaluation scales of each degree with respect to each bottom index are established according to previous studies (Burel et al., 2013), related rules (e.g. CCS, 2013; CCS, 2015; IMO, 2015), guidelines (e.g. DNV GL, 2014; ISO, 2015), standards (e.g. ISO, 2010), as well as in depth discussion with three domain experts mentioned in Section 4.1. Taking the index C6 (Regulatory regime for daily operations) as an example, the five-degree evaluation scale is interpreted as following. 'Best' represents a full and sound regulatory regime as well as very strict enforcement; 'Good' represents a satisfied regulatory regime and strict enforcement; 'Average' represents an acceptable regulatory regime and normal enforcement; 'Poor' represents a fair regulatory regime and weak enforcement; 'Worst' means that there is no suitable regulatory regime at present. Similarly, other evaluation scales in terms of the five grades can be defined as well, and they are distributed together with the questionnaire to respondents as reference for the evaluation of those indicators from the lowest level. The same set of five-degree grades (Best, Good, Average, Poor and Worst) is also applied to the second and top level. Regarding the mapping rules between different levels, this study assumes that the evaluation results of each grade from the lower level are fully transformed to the associated same grade in the upper level. For example, the 'good' at the lower level is only transformed to 'good' at its higher level, without any share distributed to other grades.

4.3 Data collection and evaluation

Based on the five-degree evaluation scales, indexes in the bottom level can be assessed according to the judgments of experts. These judgments are collected from questionnaires distributed to the domain experts who worked in the administrative, industrial or academic environments and are from maritime shipping companies, maritime universities, Classification Societies (e.g. China Classification Society (CCS), Lloyd's Register), local maritime safety administrations, and other relevant organizations in the field. These experts have rich working experience and are familiar with the development progress of LNG fuelled ships with regard to various aspects of this research, like construction of LNG fuelled ships, maritime administration, dual fuel engines, and natural gas industry. Considering their similar background including qualifications and working experience, these experts are given the same weights when merging their judgments. The combined results are expressed in the form of the distribution of brief degrees for each grade, namely, (W_B, W_G, W_A, W_P, W_W), where $\{W_B, W_G, W_A, W_P, W_W\} \subseteq [0, 1]$, and $W_B+W_G+W_A+W_P+W_W \leq 1$. W_B, W_G, W_A, W_P and W_W represent the weights distributed to grade Best, Good, Average, Poor and Worst, respectively. If the sum of the weights is smaller than 1, it means that the judgement is incomplete and uncertainty in input data exists, and the weight of uncertainty (unknown parts) is represented by $W_{unknown}$. For example, the result ($0.2W_G$, $0.7W_A$) represents a judgment according to which 20% are good, 70% are average, and a 10% uncertainty remains. By this way, the judgments of all indexes in the bottom level can be obtained. For example, the evaluation results of indexes in the bottom level for China are shown in Table 6.

Table 6 Distribution of the brief degrees of the indexes in the index level in China

Criteria level	**Index level**	**Brief degree**
Strategy	Support from the government	(0.214, 0.186, 0.243, 0.271, 0)
	Transport-related development strategy	(0.229, 0.157, 0.5, 0.014, 0)
	Energy-related development strategy	(0.257, 0.229, 0.4, 0.014, 0)
Regulation	Pollutant emission provision and limitation	(0.329, 0.129, 0.114, 0.229, 0.129)
	Ship design and construction rules	(0.314, 0.229, 0.043, 0.286, 0.043)
	Regulatory regime for daily operations	(0.171, 0.243, 0.1, 0.229, 0.2)
Economics	LNG fuelling/refuelling costs	(0.129, 0.214, 0.343,0.2, 0.043)
	Facilities maintenance costs	(0.143, 0.129, 0.414, 0.229, 0)
	Crew training for LNG fuelled ships	(0.171, 0.143, 0.314, 0.2, 0.071)
	Ships construction/conversion costs	(0.2, 0.257, 0.186, 0.214, 0.057)
Technology	LNG storage and supply systems	(0.243, 0.314, 0.214, 0.114, 0)
	Machinery arrangement of engine room	(0.343, 0.186, 0.243, 0.129, 0)
	Monitoring, control and safety systems	(0.314, 0.286, 0.171, 0.114, 0)
	Key technologies of marine engine	(0.171, 0.257, 0.186, 0.243, 0.043)
	LNG loading/unloading equipment	(0.214, 0.243, 0.286, 0.171, 0.029)
Infrastructure	LNG receiving terminals	(0.343, 0.114, 0.229, 0.214, 0)
	LNG bunkering facilities	(0.271, 0.114, 0.129, 0.3, 0.129)
	LNG storage facilities	(0.286, 0.243, 0.157, 0.129, 0.129)
	LNG production plants	(0.343, 0.257, 0.171, 0.114, 0)

Eq. (3) and (4) are used to combine the evaluation result in Table 6 form the bottom level to the criteria level. Based on the same algorithm on evidence fusion, the calculation can be achieved through the Intelligent Decision Systems (IDS), a decision support software product developed by Yang (2011). The results are shown in Table 7.

Table 7 Distribution of the brief degrees of the indexes in the criteria level

Index	**Country**	Worst	Poor	Average	Good	Best	Unknown
Strategy	China	0	13.62%	37.19%	18.31%	22.82%	8.06%
	Norway	1.89%	5.19%	26.91%	38.59%	20.68%	6.73%
	USA	0	11.04%	51.02%	17.24%	11.35%	9.36%
Regulation	China	11.65%	25.33%	8.41%	18.97%	29.34%	6.3%
	Norway	0	3.16%	7.3%	27.32%	55.88%	6.34%
	USA	0	8.02%	17.59%	39.62%	26.33%	8.44%
Economics	China	4.03%	21.25%	31.49%	19.86%	16.03%	7.34%
	Norway	0	18.07%	33.72%	26.98%	14.05%	7.18%
	USA	0	3.69%	25.62%	39.97%	22.56%	8.16%
Technology	China	1.52%	16.01%	20.7%	27.22%	25.63%	8.92%
	Norway	0	0.55%	28.73%	41.63%	20.83%	8.27%
	USA	0	1.44%	31.1%	35.95%	22.61%	8.9%
Infrastructure	China	9.22%	22.31%	15.41%	16.07%	30.9%	6.08%
	Norway	0	1.46%	13.6%	16.49%	62.58%	5.87%
	USA	0.41%	10.44%	27.51%	26.13%	25.94%	9.58%

Furthermore, the evaluation of the goal level can be achieved in a similar way, and the distribution of the brief degrees of the evaluation on the goal level of the three countries is shown in Figure 2.

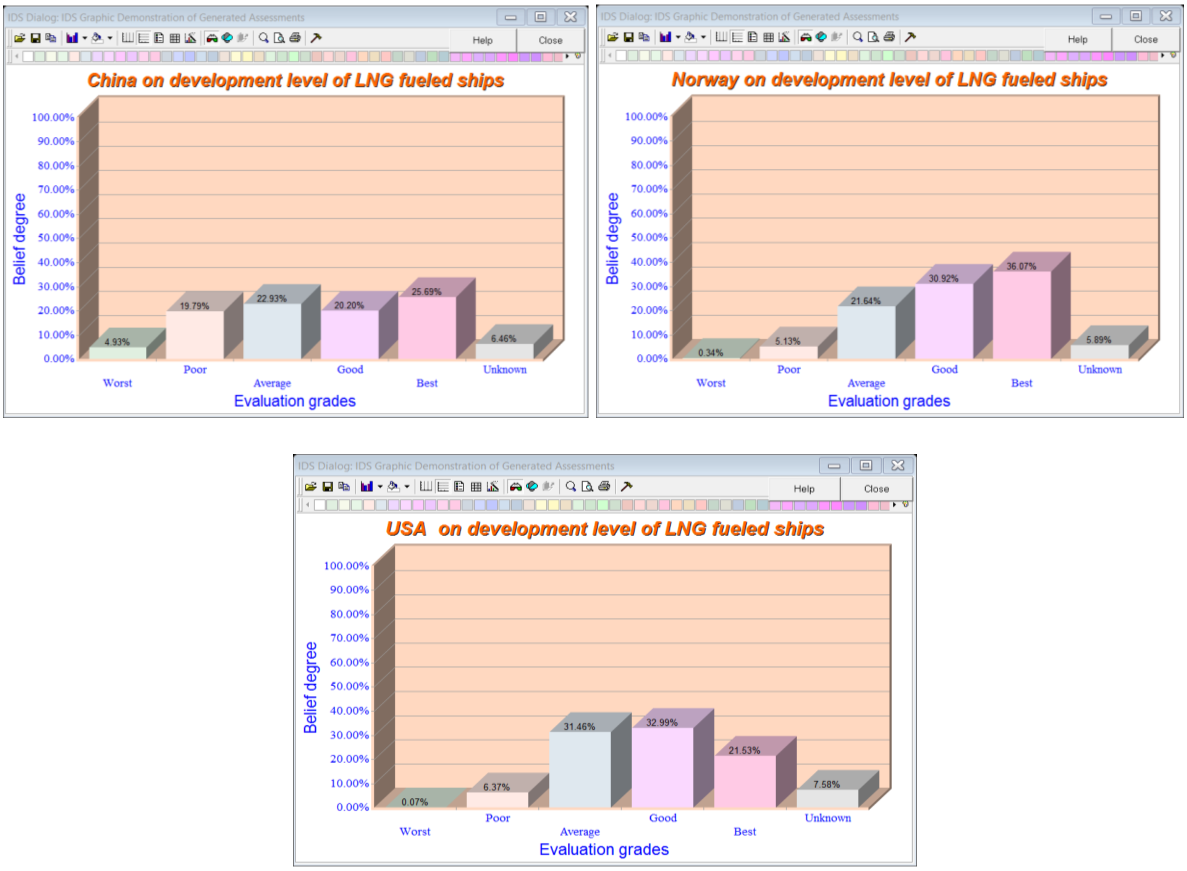


Figure 2 Distribution of the brief degrees of the evaluation of the goal level

4.4 Calculation and analysis of utility values

In order to compare the development of LNG fuelled ships among three countries, the utility function is used to transfer the distribution of the brief degrees of the goal level into crisp values for the easiness of ranking. According to the Eq. (9), the utility of each grade can be calculated and shown below. The final utility values of the development of LNG fuelled ships can be obtained through Eq. (10). Therefore, the higher the utility value is, the better the development of the LNG fuelled ships in that country.

$u(H_W)=\frac{1-1}{5-1}=0$, $u(H_P)=\frac{2-1}{5-1}=0.25$, $u(H_A)=\frac{3-1}{5-1}=0.5$, $u(H_G)=\frac{4-1}{5-1}=0.75$, and $u(H_B)=\frac{5-1}{5-1}=1$.

The unknown parts existing in the evaluation represent the epistemic uncertainties from experts, which may result from various reasons, such as the lack of information or knowledge, not fully understanding of the system, and being unconfident of their judgments. These parts of the judgments can be distributed into either the Best or Worst grades to calculate the potential maximum or minimum utility values, and then the average one can be achieved through sum average of the maximum and minimum values, which is expressed as $(u_{min}(E)+u_{max}(E))/2$. In this way, the potential maximum and minimum utility values, as well as the average utility values can be calculated. The evaluation results of the indexes in criteria level are summarized in Table 8, and their rankings in terms of average utility values under each criterion are presented in Figure 3.

Table 8 Utility values of the indexes in the criteria level

Index	**Country**	**Max value**	**Min value**	**Ave value**
Strategy	China	0.6660	0.5856	0.6258
	Norway	0.7110	0.6438	0.6774
	USA	0.6189	0.5255	0.5722
Regulation	China	0.6040	0.5410	0.5725
	Norway	0.8715	0.8081	0.8398
	USA	0.7368	0.6422	0.6895
Economics	China	0.5932	0.5198	0.5565
	Norway	0.6285	0.5567	0.5926
	USA	0.7443	0.6627	0.7035
Technology	China	0.6932	0.6040	0.6486
	Norway	0.7481	0.6655	0.7068
	USA	0.7438	0.6548	0.6993
Infrastructure	China	0.6232	0.5624	0.5928
	Norway	0.8797	0.8211	0.8504
	USA	0.7149	0.6189	0.6669

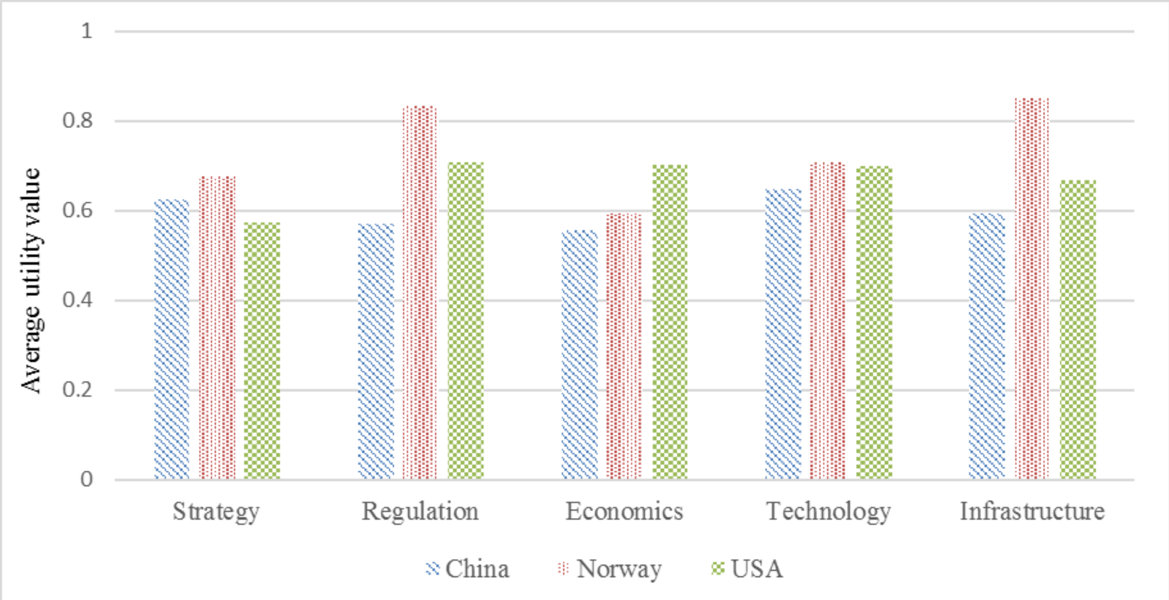


Figure 3 Average utility values of the indexes in criteria level in different countries

It can be seen from the Figure 3 that except for the economics aspect (where the USA ranks the first), Norway has the best performance in all the other aspects, including strategy, regulation, technology, and infrastructure, followed by the USA and China. The difference between their performances becomes hugely significant as far as the development of regulation and infrastructure is concerned, against which the development in Norway is much better than that of the other two countries. Between China and USA, the latter performs better in many cases, except for the development of strategy.

Based on the evaluation results from the criteria level, the utility values of the overall development level of LNG fuelled ships in different countries can be calculated and then ranked according to the average ones, as shown in Table 9. The results are further depicted in Figure 4.

Table 9 Utility values of the development level of LNG fuelled ships in different countries

	Max value	**Min value**	**Ave value**	**Rank**
China	0.6371	0.5725	0.6048	3
Norway	0.7727	0.7137	0.7432	1
USA	0.7081	0.6307	0.6694	2

In terms of the overall development of LNG fuelled ships, Norway ranks the first with an average utility value of 0.7432, followed by the USA with an average utility value of 0.6738, and China, with an average utility value of 0.6048, as shown in Figure 4. However, it is noteworthy that uncertainties existing in the evaluation which results in the possible maximum and minimum values, may influence the final ranking result. In this case study, Norway is always ranked first, because its minimum utility value (i.e. 0.7137) is higher than the maximum one of the other two countries. However, the maximum value of China is 0.6371, which is higher than the minimum value of the USA (i.e. 0.6307). It means that there remains a possibility that China performs better fuelled than USA. Furthermore, regarding the uncertainties, it is also worth noting that the evaluations on USA are involved with the highest level of uncertainty based on the experts' judgments fuelled though it is less than 10%.

The above results can aid policy makers to find the weaknesses needing investment with priority so that it can rationalize the development strategy of a nation's LNG fuelled ships.

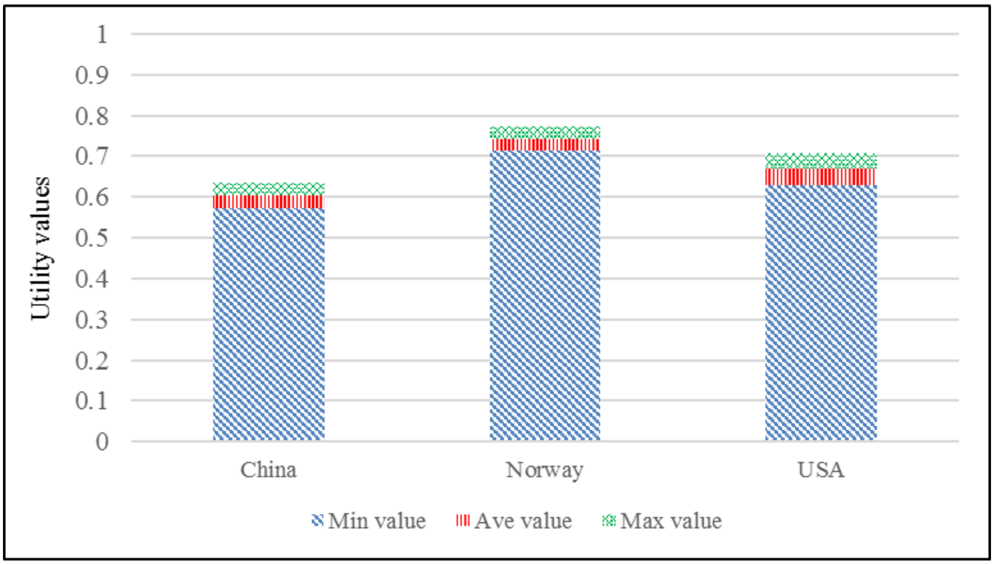


Figure 4 Ranking of alternatives on development level of LNG fuelled ships

4.5 Sensitive analysis

The sensitivity analysis is conducted to test the robustness of the model and the logicality of the above analysis results according to three axioms introduced in Section 3, and the validation of the model is achieved through the comparison between evaluation results and two hypotheses. Firstly, it is required to clarify the relationship between the average utility values of development levels of LNG fuelled ships (referred to as *utility values*) and their associated attributes (i.e. the lowest level indexes). As the assessments grades of all indexes in the lowest level hold a positive correlation with the *utility values*, the relationship can be easily identified and described as that the *utility values* is higher, if the assessment grade on each index in the lowest level is better. Next, a belief degree of 0.1 is reassigned in each index and moved toward the maximal increment of *utility values*. If the model reflects the logical reasoning, the *utility values* will increase accordingly. For example, if the brief degree of the "C1 Support from the government" belonging to "best" increases by 0.1, and correspondingly, the brief degrees of it belonging to "poor" decrease by 0.1, then the *utility values* of China increases from 0.6048 to 0.6136, the *utility values* of Norway increases from 0.7432 to 0.7501, and the *utility values* of the USA increases from 0.6694 to 0.6769. The similar studies have been conducted to investigate the influence of the other lowest level indexes (See Appendix 1). All the results obtained keep harmony with **Axiom 1** in Section 2. Such a sensitivity study reveals that the *utility values* of all countries are sensitive to indexes. However, the study based on point changes instead of interval variation (i.e. [0, 0.1]) does not well disclose the influence magnitude of the belief degree changes of the lowest indexes to the *utility values* of different countries. To study such influence magnitude, a graphical form of the sensitivity analysis based on an interval [0, 0.1], where the change of a belief degree from 0 to 0.1 with a step of 0.02 is used for each factor toward the maximal increment of the *utility values*. From Figure 5, it is clear that the influence magnitudes of the belief degree changes of the lowest indexes to the *utility values* are significantly different and such influence magnitudes closely follow the weight distributions of the lowest level indexes in Table 3. This is consistent with **Axiom 2** introduced in Section 2.

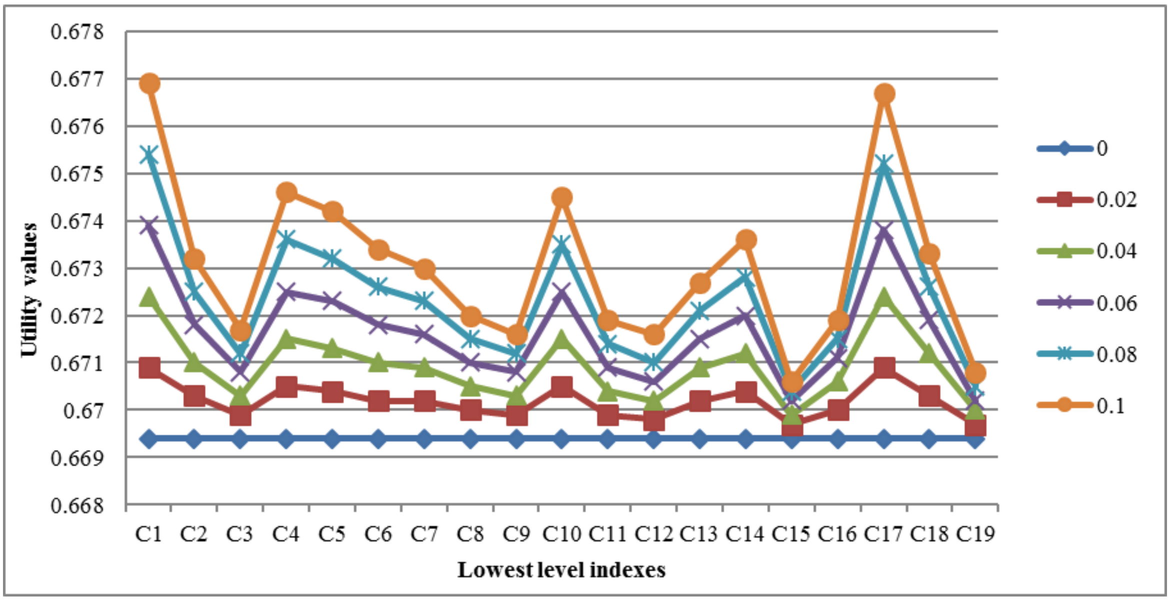


Figure 5 Sensitivity analysis of the *utility values* of the USA

While the discussion above mainly focuses on the belief degrees, in the next step, an analysis will be carried out on the effect of the variation of the lowest level indexes to the *utility values* of the three countries. The variation indicates the various combinations of the lowest level indexes. For example, Table 10 is taken as an illustration of the study of the influence magnitude of 15 different combinations of the four lowest level indexes (under criteria *Infrastructure*) to the *utility values* of the three countries. According to **Axiom 3** described in Section 2, if the model reflects the reality, then the *utility values* of the three countries associated with x factors (evidence) will be always smaller than the one from x-y ($y \in x$) factors (sub-evidence). This can be examined by comparing the *utility values* in the chosen rows in Table 9. For example, Row 12 is chosen as the evidence to investigate the accuracy of the model. Then those rules related to its sub-evidence can be identified to include Rows 2, 3, 4, 6, 7 and 9. Comparing all relevant *utility values* (i.e. the *utility values* of *China* in Row 12 equals 0.6241, which is obviously bigger than 0.6183, the one in Row 6), it can be claimed that for the investigation of Row 12, the component *Infrastructure* of the model is validated to be sound. Similarly, a comprehensive analysis in terms of all five criterial level indexes (which are *Strategy, Regulation, Economics, Technology* and *Infrastructure*) has been carried out, and the reasonable results being in line with **Axiom 3** are considered as a piece of evidence of the soundness and logicality of the whole model.

Table 10 Sensitivity analysis of the variation of the lowest level factors under *Infrastructure*

Row	***Infrastructure***				***Utility values***		
(No)	*C16*	*C17*	*C18*	*C19*	*China*	*Norway*	*USA*
1	0	0	0	0	0.6048	0.7432	0.6694
2	1	0	0	0	0.6079	0.7454	0.6719
3	0	1	0	0	0.6152	0.7487	0.6767
4	0	0	1	0	0.6108	0.7465	0.6733
5	0	0	0	1	0.6068	0.7444	0.6708
6	1	1	0	0	0.6183	0.7509	0.6791
7	1	0	1	0	0.6139	0.7488	0.6758
8	1	0	0	1	0.6099	0.7467	0.6732
9	0	1	1	0	0.6209	0.7518	0.6805
10	0	1	0	1	0.6172	0.7499	0.6780

11	0	0	1	1	0.6060	0.7477	0.6747
12	1	1	1	0	0.6241	0.7540	0.6830
13	1	1	0	1	0.6203	0.7521	0.6805
14	0	1	1	1	0.6230	0.7530	0.6819
15	1	1	1	1	0.6261	0.7551	0.6844

"1"means a 10% reassignment of belief degrees in each factor moving toward the maximal increment of *utility values*.

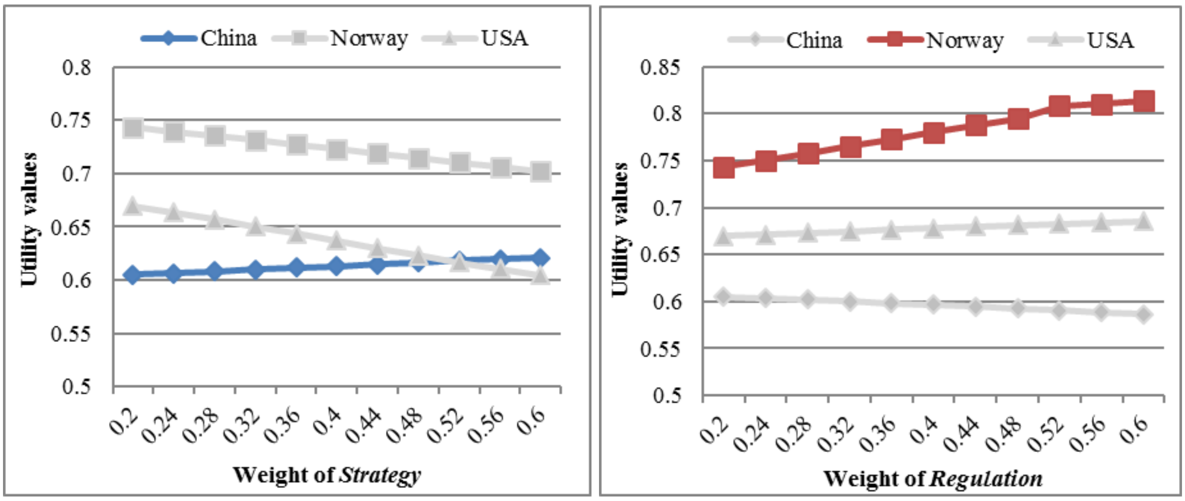
Having completing the sensitivity analysis of the model based on three well-studied axioms, the remainder of this section will analyse the variation trend of the *utility values* in terms of the change of weights of criteria level. Knowing that the increment/decrement of the weight of a certain criterion will result in the corresponding increment/decrement of average utility values of development levels of LNG fuelled ships in a country that performs well in terms of the selected criterion, some hypotheses for this study are proposed to validate the proposed model, based on the clues on the real-life situation of the development of LNG fuelled ships worldwide observed from related government documents, project reports (Lloyd's Register, 2012) and relevant researches (e.g. Wan et al., 2015).

Hypothesis 1. The increment of the weight of the *Strategy* will result in the increment of the average utility values of development levels of LNG fuelled ships in China.

Hypothesis 2. The increment of the weight of the *Regulation* will result in the increment of the average utility values of development levels of LNG fuelled ships in Norway.

Although the weights of criteria level factors are equal according to experts for the consideration of universality of the model in this study. However, it is another situation in real life cases as various factors existing affect the policy-making process in terms of the development of LNG fuelled ships. Emphases on different aspects usually vary in different countries, and also it will be difficult to maintain a same development process in every aspect with limited resources. For example, in China, the technology of LNG fuelled ships lags behind compared to other European countries (see Table 2), but it has enacted a series of supporting policies to promote the development of LNG fuelled ships and related industries, which may result in its relative better performance regarding the strategy criteria compared to that in other aspects. Following similar evidences, two hypotheses are proposed in Section 2 based on the published materials relating to the development of LNG fuelled ships to validate the model. In this study, the weights of indexes are reassigned, in which weight of the targeted index is increased from 0.2 to 0.6 with a step of 0.04, while that of other four indexes are decreased simultaneously with a step of 0.01. For example, the initial weight of *Strategy* is 0.2, when it increases from 0.2 to 0.24, the weights of other four indexes will be decreased to 0.19. In order to test the hypotheses in Section 2, the *Strategy* and *Regulation* are selected as targeted indexes whose weights will be increased, and the corresponding change of *utility values* are recorded and represented, as shown in Figure 6a and 6b.

As the weight of *Strategy* increases, the *utility values* of China show a growing trend, increasing from 0.6048 to 0.6208; along with the increment of weight of *Infrastructure*, the utility values of Norway increases from 0.7432 to 0.8138. This variation can be seen clearly from the Figure 6. Based on that, it can be claimed that the results obtained are in harmony with the **Hypothesis 1** and **2** proposed in Section 2, verifying the rationality and feasibility of the SRETI model in terms of the evaluation of development of LNG fuelled ships.



a) b)

Figure 6 Variation trends of utility values with change of weights

5. Conclusion

This paper proposes a novel model for the evaluation of the development of LNG fuelled ships. Altogether 19 indexes are selected from the aspects of strategy, regulation, economics, technology and infrastructure. A case study of China, Norway and the USA has been conducted to illustrate and validate the proposed model through comparison analysis and sensitivity analysis. Overall, the evaluation results match the axioms, as well as two hypotheses developed based on the investigation of the development situation of LNG fuelled ships worldwide, which supports the correctness and feasibility of the proposed model. Besides, the ER approach is applied to deal with the evaluation results of the indexes which are expressed by assessment grading with a brief structure. The main advantage of using ER approach is that it is able to synthesise subjective judgments from experts taking into account uncertainties which may result from the lack of reliable data source, industries experience, or academic bias. The novel model and flexible methods presented in this paper can not only be used to comparatively analysis the development level of LNG fuelled ships in different countries, but also be used to evaluate the development process of LNG fuelled ships in a specific area during a certain time of period, so as to offer stakeholders with helpful reference for the decision making. Moreover, the proposed model can be further tailored for the evaluation of development of other industries with emerging technologies, where a higher level of questionnaire feedbacks and interviews with a larger number of experts are expected to further improve the results.

Acknowledgement

The authors would like to thank the National Nature Science Foundation of China (51579203) and the EU FP7 Marie Curie IRSES project “ENRICH” (612546) for their financial support for this research. In addition, the authors would like to thank the experts and anonymous respondents for their valuable contribution to this study.

Reference

Anderson, D.R., Sweeney, D.J., and Williams, T.A., 2003. An Introduction to Management Science: Quantitative Approaches to Decision Making, 10th Edition. South-Western, Nelson, Canada.

Altunbulak, N., 2009. Maritime Transportation Security against Terrorism and Human Smuggling. Transportation Security against Terrorism, 54, p.75.

Blikom, L. P., 2012. Status and way forward for LNG as a maritime fuel. Australian Journal of

Maritime and Ocean Affairs, 4(3), pp. 99-102.

Burel, F., Taccani, R. and Zuliani, N., 2013. Improving sustainability of maritime transport through utilization of Liquefied Natural Gas (LNG) for propulsion. Energy, 57, pp.412-420.

China Classification Society, 2013. Rules for natural gas fueled ships. Accessible at: http://www.ccs.org.cn/ccswz/font/fontAction!article.do?articleId=ff808081412b4cca01412f8cf7d50066

China Classification Society, 2015. Rules for liquefied natural gas bunkering vessel. Accessible at: http://www.ccs.org.cn/ccswzen/font/fontAction!article.do?articleId=ff8080815382213e015382894b1100a5

Chin, K., J. B. Yang, M. Guo, and, P. LAM, 2003. An Evidential- Reasoning- Interval- Based Method for New Product Design Assessment. IEEE Transactions on Engineering Management, 56(1), pp. 142-156.

DNV GL, 2014. Development and operation of liquefied natural gas bunkering facilities. DNV GL-RP-0006.

Dyson, R.G., 2004. Strategic development and SWOT analysis at the University of Warwick. European journal of operational research, 152(3), pp.631-640. w

Fu, S., Yan, X., Zhang, D., Li, C. and Zio, E., 2016. Framework for the quantitative assessment of the risk of leakage from LNG-fueled vessels by an event tree-CFD. Journal of Loss Prevention in the Process Industries, 43, pp.42-52.

Global News. Global development of LNG fuelled ships. LNG market. http://yeslng.com/p/6669. Accessed Sep. 25, 2015.

Guo, R., and H. Z. Yang, 2012. Roadmap of renewable energy industry development in Chongming Eco-island. Journal of Tongji University (natural science), 40(8), pp. 1204-1209.

Ha, H. and Coghill, K., 2006. E-Government in Singapore-A Swot and Pest Analysis. Asia-Pacific Social Science Review, 6(2), pp.103-130.

Halla, F. A., 2007. SWOT analysis of strategic urban development planning: The case of Dares Salaam city in Tanzania. Habitat International, 31(1), pp. 130-142.

Heir H, Bjornsen J, Hosoien A, and Eide, T.L., 2011. Infrastructural challenges for LNG fuelled vessels in the SECA. Unpublished report of course TPG4140 Natural Gas, Distribution, Norwegian University of Science and Technology, Norway

International Maritime Organization, 2009. Report of the International Maritime Organization, MEPC 59/INF.10, Second IMO GHG study 2009

International Maritime Organization, 2015. International Code of Safety for Ships using Gases or other Low-flashpoint Fuels. IGF Code, MSC. 391(95).

International Standardization Organization, 2010. Installation and equipment for liquefied natural gas¡ªShip-to-shore interface and port operations. ISO 28460:2010.

International Standardization Organization, 2015. Guidelines for systems and installations for supply of LNG as fuel to ships. ISO/TS 18683:2015.

Jiang, Q. Z., Y. M. Xu, W. J. Xin, Z. Z. Song, Q. Q. Song, and M. Ke, 2012. SWOT-AHP hybrid model for vehicle lubricants from CNPCLC. China Petro Science, 9(4), pp. 558-564.

Jiang, T., 2014. Environmental pollution prevention and governance in Tianjin Port, Journal of Transportation Information and Safety, 32, pp. 102-107.

Kajanus, M., J. Kangas, and M. Kurttila, 2004. The use of value focused thinking and the A'WOT hybrid method in tourism management. Tourism Management, 25, pp. 499-506.

Kumar, S., H. T. Kwo, and K. H. Choi., 2011. Current status and future projections of LNG demand and supplies: A global prospective. Energy Policy, 39, pp. 4097-4104.

Kumar, S., H. T. Kwon, K. H. Choi, W. Lim, J. H. Cho, K. Tak, and I. Moon., 2011. LNG: An eco-friendly cryogenic fuel for sustainable development. Applied Energy, 88(12), pp. 4264-4273.

Lloyd's Register, 2012. LNG-fuelled Deep Sea Shipping- The outlook for LNG bunker and LNG-fuelled newbuild demand up to 2025. August 2012, published by Lloyd's Register. Available on line: http://www.lr.org/en/_images/21335922_lr_bunkering_study_final_for_web_tcm155-243482.pdf

Liu, J., J. B. Yang, D. Runa, L. Martinez, and J. Wang, 2008. Self-tuning of fuzzy belief rule bases for engineering system safety analysis. Annals of Operations Research, 163(1), pp. 143-168.

Luce, M.F., Bettman, J.R. and Payne, J.W., 1997. Choice processing in emotionally difficult decisions. Journal of Experimental Psychology: Learning, Memory, and Cognition, 23(2), p.384.

Lv, A. T., C. B. Zhang and A. H. Shi., 2009. Evaluation index system of energy-saving and emission-reducing for Shandong harbor and shipping system. Journal of Transport Information and Safety, 27(6), pp. 52-54.

Ma, L.W., J. Geng, W. Q. Li, P. Liu, and Z. Li., 2013. The development of natural gas as an automotive fuel in China. Energy Policy, 62, pp. 531-539.

Nordtun, T., 2012. Sailing on LNG from concept to reality. Gas fuelled ships conference, Bergen, Norway.

Oskar, L., 2008. Turning the page in ship propulsion, by switching to LNG, Wärtsilä, Gas as fuel for propulsion of ships- status and perspectives, Copenhagen, Denmark.

Parsons, M. G., P. J. O'Hern, and S. J. Denomy., 2012. The potential conversion of the US great lakes steam bulk carriers to liquefied natural gas propulsion - Initial report. Journal of Ship Production and Design, 28(3), pp. 97-111.

Saaty, T.L. 1980, The Analytic Hierarchy Process. McGraw Hill International New York.

Shin, M.W., Shin, D., Choi, S.H. and Yoon, E.S., 2008. Optimal operation of the boil-off gas compression process using a boil-off rate model for LNG storage tanks. Korean Journal of Chemical Engineering, 25(1), pp.7-12.

Tahernejad, M. M., R. Khalokakaie, and M. Ataei, 2013. Determining proper strategies for Iran's dimensional stone mines: a SWOT-AHP analysis. Arabian Journal Geoscience, 6(1), pp. 129-139.

Wan, C. P., X. P. Yan, D. Zhang, J. Shi, S. S. Fu, and AKY. Ng., 2015. Emerging LNG-fuelled ships in the Chinese shipping industry: a hybrid analysis on its prospects. WMU Journal of Maritime Affairs, 14(1), pp. 43-59.

Wang, J., 2013. LNG fuelled ships become the upstart of natural gas. China Securities Journal, A13.

Wang, S.Y., and T. Notteboom., 2013. LNG as a ship fuel: perspectives and challenges. Port Technology International, 60, pp. 15-17.

Wikipedia, 2016. Liquefied natural gas. https://en.wikipedia.org/wiki/Liquefied_natural_gas#Storage Accessed Aug. 5, 2016

Xu, D. L., and J. B. Yang, 2005. Intelligent decision system based on the evidential reasoning approach and its applications. Journal of Telecommunications and Technology, 3, pp. 73-80.

Yang, J. B., 2001. Rule and Utility Based Evidential Reasoning Approach for Multiattribute Decision Analysis under Uncertainties. European Journal of Operational Research, 131(1), pp. 31-61.

Yang, J. B., and D. L. Xu, 2013. Evidential reasoning rule for evidence combination. Artificial Intelligence, 205, pp. 1-29.

Yang, Z.L., Wang, J., Bonsall, S., and Fang, Q.G., 2009. Use of fuzzy evidential reasoning in maritime security assessment. Risk Analysis, 29(1), pp. 95-120.

Zhai, X. M., H. S. Wang, and F. Feng., 2014. Multi-Physics Coupling Method and Applications of Fluid-Structure Interaction on LNG Storage Tanks. 11th World Congress on Computational Mechanics (WCCM XI), Barcelona, Spain.

Zhou, S. H., X. Shen, and X. J. Liu., 2013. Prospect of LNG application to inland water transportation in China. Natural Gas Industry, 33(2), pp. 81-89.

Appendix 1. Sensitivity analysis of the utility value of three countries given the variation of the lowest level indexes in [0, 0.1] at a step of 0.02

	0	**0.02**	**0.04**	**0.06**	**0.08**	**0.1**	**0**	**0.02**	**0.04**	**0.06**	**0.08**	**0.1**
CN	0.605	0.607	0.608	0.610	0.612	0.614	0.605	0.606	0.607	0.607	0.608	0.609
NO	0.743	0.745	0.746	0.748	0.749	0.750	0.743	0.744	0.746	0.747	0.748	0.749
US	0.669	0.671	0.672	0.674	0.675	0.677	0.669	0.670	0.671	0.672	0.673	0.673
C1. Support from the government							C2. Transport-related development strategy					
CN	0.605	0.606	0.606	0.607	0.607	0.608	0.605	0.607	0.609	0.610	0.612	0.614
NO	0.743	0.744	0.744	0.745	0.745	0.746	0.743	0.744	0.745	0.746	0.747	0.747
US	0.669	0.670	0.670	0.671	0.671	0.672	0.669	0.671	0.672	0.673	0.674	0.675
C3. Energy-related development strategy							C4. Pollutant emission provision and limitation					
CN	0.605	0.606	0.608	0.609	0.610	0.611	0.605	0.606	0.607	0.608	0.610	0.611
NO	0.743	0.744	0.745	0.745	0.746	0.747	0.743	0.744	0.745	0.746	0.746	0.747
US	0.669	0.670	0.671	0.672	0.673	0.674	0.669	0.670	0.671	0.672	0.673	0.673
C5. Ship design and construction rules							C6. Regulatory regime for daily operations					
CN	0.605	0.606	0.607	0.608	0.609	0.610	0.605	0.606	0.606	0.607	0.608	0.609
NO	0.743	0.744	0.745	0.746	0.747	0.748	0.743	0.744	0.745	0.745	0.746	0.747
US	0.669	0.670	0.671	0.672	0.672	0.673	0.669	0.670	0.671	0.671	0.672	0.672
C7. LNG fuelling/refuelling costs							C8. Facilities maintenance costs					
CN	0.605	0.606	0.606	0.607	0.608	0.608	0.605	0.606	0.608	0.609	0.610	0.612
NO	0.743	0.744	0.744	0.745	0.745	0.746	0.743	0.744	0.745	0.746	0.748	0.749
US	0.669	0.670	0.670	0.671	0.671	0.672	0.669	0.671	0.672	0.673	0.674	0.675
C9. Crew training for LNG fuelled ships							C10. Ships construction/conversion costs					
CN	0.605	0.606	0.606	0.607	0.608	0.609	0.605	0.605	0.606	0.607	0.607	0.608
NO	0.743	0.744	0.744	0.745	0.745	0.746	0.743	0.744	0.744	0.744	0.745	0.745
US	0.669	0.670	0.670	0.671	0.671	0.672	0.669	0.670	0.670	0.671	0.671	0.672
C11. LNG storage and supply systems							C12. Machinery arrangement of engine room					
CN	0.605	0.606	0.607	0.608	0.608	0.609	0.605	0.606	0.608	0.609	0.610	0.611
NO	0.743	0.744	0.744	0.745	0.746	0.746	0.743	0.744	0.745	0.746	0.736	0.747
US	0.669	0.670	0.671	0.672	0.672	0.673	0.669	0.670	0.671	0.672	0.673	0.674
C13. Monitoring, control and safety systems							C14. Key technologies of marine engine					
CN	0.605	0.605	0.606	0.606	0.606	0.607	0.605	0.605	0.606	0.607	0.607	0.608
NO	0.743	0.743	0.744	0.744	0.744	0.744	0.743	0.744	0.744	0.745	0.745	0.745
US	0.669	0.670	0.670	0.670	0.670	0.671	0.669	0.670	0.671	0.671	0.672	0.672
C15. LNG loading/unloading equipment							C16. LNG receiving terminals					
CN	0.605	0.607	0.609	0.611	0.613	0.615	0.605	0.606	0.607	0.608	0.610	0.611
NO	0.743	0.744	0.745	0.747	0.748	0.749	0.743	0.744	0.745	0.745	0.746	0.747
US	0.669	0.671	0.672	0.674	0.675	0.677	0.669	0.670	0.671	0.672	0.673	0.673
C17. LNG bunkering facilities							C18. LNG storage facilities					
CN	0.605	0.605	0.606	0.606	0.606	0.607	“CN” represents China, “NO” represents Norway, “US” represents the USA.					
NO	0.743	0.743	0.744	0.744	0.744	0.744						
US	0.669	0.670	0.670	0.670	0.671	0.671						
C19. LNG production plants												