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Evaluation of liquefied natural gas bunkering port selection

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Given environment regulations on emissions from ships, shipping companies have sought alternative fuel ships, such as LNG-powered vessels, which may give rise to growth in liquefied natural gas (LNG) bunkering ports. Because demand for LNG-powered vessels is expected to increase, it is worth assessing the factors that lead to the selection of LNG bunkering ports in LNG bunkering industries. However, a lack of academic research exists in the field of LNG bunkering. This paper employs a second-stage empirical analysis approach that selects criteria for shipping companies' selection of a LNG bunkering port through a literature review and interviews, and then adopts a fuzzy-AHP methodology to reveal the priority of the LNG bunkering port selection criteria in LNG bunkering decision making. The results indicate that most shipping companies decide on a LNG bunkering port with a stronger emphasis on safety/security or port services rather than port reputation. This paper offers invaluable policy implications for governments and port authorities that plan to build and operate LNG bunkering ports in the near future.

Keywords: Liquefied natural gas; LNG bunkering; seaport; port selection; fuzzy-AHP

1. Introduction

Globally, the environmental crisis caused by global warming has created the serious problem of increasing greenhouse gases, sulfur oxides, nitrogen oxides, carbon dioxide (CO2), and particulate matter. As a result, demand for responses to climate change and environmental protection is increasing (Zhu, Li, and Lam 2017). This demand has strengthened environmental regulations on air pollutant emissions from ships managed by international organizations, such as Tier III of the International Maritime Organization (IMO) (Yang 2015). Liquefied natural gas (LNG) is a potential solution to meeting these stronger regulations. Eyring et al. (2005) estimated that between 1950 and 2001, CO2 emissions attributable to shipping increased more than four-fold, a change that has significant implications for the growth of shipping-related greenhouse gas emissions (Wen et al. 2017; Lai et al. 2013). Regarding greenhouse gas emissions from ships, LNG is cleaner burning than heavy diesel oil (HDO) and marine gas oil (MGO) because of its negligible sulfur content (Lloyd's Register 2012). Zhu, Li, and Lam (2017) noted that LNG as a fuel has the advantages of longer equipment life and lower maintenance costs than exhausted gas scrubber and marine diesel oil (MDO)/MGO, which are currently considered alternatives. Additionally, LNG can reduce average particulate matter emissions by 94%.

The IMO's regulations for a 0.5% m/m (mass/mass) sulfur cap in 2020 for marine fuels and emission control areas (ECA) in various regions, such as the North Sea and Baltic Sea, are factors driving the growth of LNG-powered vessels (LPV) (Kotrikla, Lilas, and Nikitakos 2017; Lun et al. 2015). According to DNV (2012), under a high economic development and high environmental awareness scenario, the number of LPVs has been estimated at approximately 1,000 by 2020. In particular, combined with stricter emissions control regulations, Europe and North America are expected to experience growth in LPVs. Asia is also expected to play an important role after 2020, driven by nations with stricter regulations, such as Singapore and Hong Kong. Lloyd's Register (2014) estimated that even though high sulfur fuel oil (HFO) might remain the main fuel for shipping, the LNG quota is expected to reach 11% by 2030, equivalent to approximately 20% of today's bunker volume.

However, LNG bunkering infrastructure has been developed only in a handful of ports across the globe, particularly in the North Sea and the Baltic Sea. Although ECAs exist in these regions to comply with environmental regulations, shipping companies must operate their vessels for their businesses. Therefore, demand for LNG bunkering is increasing naturally given the increase in LPVs. Environmental regulations on ship emissions are causing shipping companies to seek vessels, such as LPVs, that use alternative fuels. This change may accelerate the growth of LNG bunkering ports. In reality, according to AG&P (2017), the global LNG bunkering market is expected to grow from $248.64 million in 2016 to $8,187.35 million by 2023, or a compound annual growth rate of 64.7%.

Various studies show that LPV demand is expected to increase (DNV 2012, TRI-ZEN 2016, LNG World Shipping 2016). It is worth evaluating the LNG bunker port selection factor in the LNG bunker industry in this situation. Furthermore, a lackof academic research exists in the field of LNG bunkering (Lloyd's Register 2012; 2014; DNV 2012), thus presenting a plausible reason for venturing deeper into the relatively uncharted field of LNG bunkering research. This study employs a second-stage approach in empirical analysis and selects criteria for a shipping company's choice of a LNG bunkering port using literature reviews and interviews. The approach then adopts a fuzzy-AHP methodology to reveal the priority of LNG bunkering port selection criteria in LNG bunkering decision making. Based on this study's results, the port policy makers or port authorities preparing the LNG bunkering port will be able to shape or come up with adequate policies for more competitive LNG ports by understanding the priorities of shipping companies when selecting LNG bunkering ports.

This paper is structured as follows. The next section reviews the relevant studies and the third section explains the methodology. The empirical analysis is shown in the fourth section. Finally, the fifth section provides discussion and concluding remarks.

2. Literature review

2.1 Port selection

The port selection problem is directly connected to port competitiveness. According to Malchow and Kanafani (2004), because competition among ports has intensified, various intermodal facilities are being improved to minimize the time that shipments are at the port. In addition, port infrastructure and superstructure are being augmented, such as expanding storage space and dredging channel depths to allow shipping companies to operate large vessels. Port selection, which focuses on customer (user) decisions, is part of customer behavior research and includes carriers/shipping companies, shippers, and freight forwarders (Brooks, Schellinkck, and Pallis 2011; Tongzon 2009). Thus, ports should provide sound facilities and services for users.

A considerable body of literature exists from various stakeholders, including shippers, shipping companies, and freight forwarders, on port attractiveness, competitiveness, efficiency, and selection using a number of methodologies. In these studies, factors that affect port selection are identified and categorized using different classification methods. Previous research on port choice models focused on the port choices made by shippers. Using seven criteria, Ugboma, Ugboma, and Ogwude (2006) presented survey results to determine the characteristics of the services that a shipper considers important when choosing a port and the prioritization of these characteristics by importance. Other studies identified and described various factors of shippers' port selection using different methodologies (Tongzon 2009; Hesse and Rodrigue 2004). Recent research has studied the choice of a port from the perspective of liners and carriers. Lirn, Thanopoulou, and Beresford (2003) suggested a set of trans-shipment port selection criteria from the viewpoint of the container carrier. Other studies that verified and described the various factors in the selection of liners or carriers used several different methodologies (Chang, Lee, and Tongzon 2008; Chou 2007).

The aforementioned literature showed that a number of common determinants exist for port selection. Details are as follows.

<insert Table 1 around here>

2.2 LNG bunkering port

LNG bunkering requires a different process from loading of HFO and MGO given the unique differences in the fuels' characteristics. The most significant difference is that LNG requires special handling relative to crude oil bunkering (ABS 2015). Generally, LNG bunkering has three solutions: truck-to-ship (TTS), ship-to-ship (STS), and terminal-to-ship via pipeline (or shore-based facility to ship) (TPS) (IACS 2016). Regarding TTS bunkering, the LNG truck is connected to the ship on the quayside, generally using a flexible hose. This bunking method is the most widely used given relatively low investment costs and the still limited demand, in combination with a lack of infrastructure. For these reasons, TTS bunkering is a sound, temporary solution for LNG bunkering. In 2008, half the Norwegian coastal ferries powered by LNG were regularly supplied by TTS bunkering, mostly overnight (Danish Maritime Authority 2012). In STS bunkering, a small bunkering vessel is connected to the ship at different locations (e.g., at the quayside, anchor, and sea). Given size limitations in some small ports, only smaller bunkering vessels may be able to operate in the port area (Swedish Maritime Technology Forum 2011). TPS bunkering is the third bunkering option in vessels moored at a pier or a floating pier and are supplied with LNG from a storage tank through a pipeline. The bunker station can be supplied by ship, truck, or pipeline and a liquefaction unit. For the TPS bunkering option, LNG is transferred from a fixed storage tank on land through a cryogenic pipeline with a flexible end piece or hose to a vessel moored to a nearby dock or pier. However, this method is less efficient than STS bunkering because vessels must travel to the bunker station and cannot simultaneously conduct cargo and bunkering operations (LNG Masterplan 2015).

Currently, U.S. shipping company TOTE Maritime operates 3,100 TEU-class LNG-powered containerships. Notably, major liners, such as UASC and CMA-CGM, also recently ordered large LNG-powered containerships. Therefore, ports may have to invest in LNG bunkering facilities to accommodate larger LNG-powered containerships. Currently, only a few ports have LNG bunkering facilities (e.g., Incheon, Long Beach, and Antwerp). Therefore, if a port invests in LNG bunkering facilities today, it may have an advantage in attracting LPVs, which will allow it to leverage the competition from other rival ports. As a representative example, the Danish government suggested LNG as an alternative fuel for ships and environmental improvement of state-owned vessels that use new lightweight materials and alternative fuels (Danish Government 2012). DNV (2012) noted that 4–7 million tons of LNG p.a. is required by 2020, which corresponds to 0.2–0.3% of global LNG production by 2010 because 1,000 more vessels will be fuelled by LNG and sailing within regions, primarily in ECAs. They recommended that LNG bunkering be evaluated for validity, such as regarding safety, the environment, regulations, logistics, technology, operations, finance, and the business perspective.

<insert Figure 1 around here>

However, the literature on LNG bunkering ports is still in its initial phase. Some existing studies explored the role of the port authority (PA) with respect to the LNG bunkering port (Wang and Notteboom 2015), LNG bunkering port development (TRI-ZEN 2016), and a feasibility evaluation of LNG bunkering (DNV 2012). Other studies verified and described the various LNG bunkering factors, including a safety management system based on a formal safety assessment (Trbojevic and Carr 2000), security risk factor table (Bajpai and Gupta 2007), and initial framework of port security assessments (Bichou 2008). Details are as bellow.

<insert Table 2 around here>

3. Methodology

3.1 Fuzzy-AHP

Decision makers frequently offer unclear responses rather than clear responses. Additionally, the conversion of qualitative choices to point approximations may not be practical (Park et al. 2018). Since the fuzzy-AHP approach can take the arrogance of decision makers into explanation, linguistic values, whose fuzzy membership functions are typically considered by triangular fuzzy numbers, are suggested to evaluate importance ratings in preference to the expected mathematical similarity method (Gumus 2009). Thus, when an uncertain pairwise comparison environment exists, fuzzy-AHP should be more appropriate and satisfactory than conformist AHP in practice (Kim and Seo 2019).

This research aims to identify the selection factors among various LNG bunkering ports using integrated AHP techniques under a fuzzy environment. Fuzzy-AHP is used to determine the preference weights of the evaluation using TFNs based on the various characteristics of LNG bunkering ports (Kaya and Kahraman 2011). This research uses TFNs for the evaluation. The steps in the fuzzy-AHP are presented as follows.

Step 1: Define scale of relative importance used in the pairwise comparison matrix

In this step, TFNs are utilized for pairwise comparisons and to find fuzzy weights because they are intuitively easy for decision makers to use and calculate. Additionally, modelling TFNs has proven to be effective in formulating decision problems for available information that is subjective and imprecise. The computational process for fuzzy-AHP is detailed as follows. A TFN can be defined by a triplet (a1, a2, a3), and the membership function $\mu_{\tilde{A}}(x)$ is defined by:

$$\mu_{\tilde{A}}(x) = \begin{cases} (x-l)/(m-l), & l \le x \le m \\ (u-x)/(u-m), & m \le x \le u \\ 0, & otherwise \end{cases} \qquad (1)$$

This research uses nine basic linguistic terms, as in Table 1, with respect to a fuzzy nine-level scale. Each membership function (scale of a fuzzy number) is defined by three parameters of the symmetric TFN—the left point, the middle point, and the right point—of the range over which the function is defined.

<insert Table 3 around here>

Step 2: Construct the fuzzy comparison matrix

In this step, pairwise comparison matrices among all criteria in the dimensions of the hierarchy system are constructed. Linguistic terms are assigned to the pairwise comparisons by asking which is the more important of each of the two dimensions, as in the following matrix $\tilde{A}$.

$$\tilde{A} = \begin{bmatrix} 1 & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ \tilde{a}_{21} & 1 & \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \cdots & 1 \end{bmatrix} = \begin{bmatrix} 1 & 1/\tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ 1/\tilde{a}_{21} & 1 & \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/\tilde{a}_{n1} & 1/\tilde{a}_{n2} & \cdots & 1 \end{bmatrix} \tag{2}$$

where,

$$\tilde{a}_{ij} = \begin{cases} \tilde{9}^{-1}, \tilde{8}^{-1}, \tilde{7}^{-1}, \tilde{6}^{-1}, \tilde{5}^{-1}, \tilde{4}^{-1}, \tilde{3}^{-1}, \tilde{2}^{-1}, \tilde{1}^{-1}, \tilde{1}, \tilde{2}, \tilde{3}, \tilde{4}, \tilde{5}, \tilde{6}, \tilde{7}, \tilde{8}, \tilde{9} \\ 1 \end{cases}$$

Step 3: Define the fuzzy geometric mean and fuzzy weight

In this step, the geometric mean technique is used to define the fuzzy geometric mean and fuzzy weights of each by Hsu and Huang (2014):

$$r_i = (a_{ij}^{1} \times a_{ij}^{2} \times \cdots \times a_{ij}^{10})^{1/n} \qquad n = 1, 2, \cdots, n \tag{3}$$

$$w_i = r_i \times (r_1 + r_2 + r_3 + \cdots + r_n)^{-1} \tag{4}$$

where a_{ij} is a fuzzy comparison value of dimension i to criterion j. Thus, r_i is a geometric mean of fuzzy comparison value of criterion i to each criterion and w_i is the fuzzy weight of the i_{th} criterion and can be indicated by a TFN.

Step 4: Determine the best non-fuzzy performance (BNP) value

It is essential to convert the weights of each criterion into non-fuzzy values through a procedure of defuzzification because they are still in the formula of fuzzy triangular values. For defuzzification, the best non-fuzzy performance (BNP) value based on the center of the area or centroid is often accepted. In this step, the BNP value for each weight (l, m, u) is determined and given by Sun (2010).

$$BNP \ \ value = \frac{[(u-l)+(m-l)]}{3} + l \tag{5}$$

Step 5: Rank the criteria

The criteria are ranked using the BNP values. The criterion with a larger BNP value is considered to have a stronger effect when compared with other criteria.

3.2 Data collection

Previous research related to the aforementioned studies was circulated among experts to obtain better insights into the problem. In this study, through interviews and the literature review, 20 detailed sub-criteria under five main criteria (cost, geography, port reputation, port service, and safety/security) were identified. The overall objective of the decision process determined for LNG bunkering port selection is on the first level of a hierarchy. The main criteria are on the second level, and the sub-criteria are on the third level of the hierarchy (see Table 2). The questionnaire for the analysis was distributed to each shipping company by referencing the world ports climate initiative (WPCI) website and the list of world LPVs (LNG World Shipping 2016). From October 13 to November 30, 2017, 134 questionnaires were distributed to the population and 24 were returned, for an approximate response rate of 18%. Depending on the consistency of the answers, 20 questionnaires were finally adopted. Twenty respondents from shipping companies consisting of CEOs, general managers, and operations managers with professional experience answered the questionnaire. According to Abduh and Omar (2012), one of the benefits of using AHP is that it does not require many respondents for the analysis, and it can be applied with just one respondent. In reality, AHP has been applied in research with small sample sizes to determine the hierarchical analysis based on experts' opinions (Peterson, Silsbee, and Schmoldt 1994; Kamal, Al-Subhi, and Al-Harbi 2001; Shen et al. 2015).

<insert Table 4 around here>

4. Empirical analysis

In this section, fuzzy-AHP is performed to determine the priority when shipping companies choose a LNG bunkering port. Selecting a LNG bunkering port is important for the following three reasons.

(1) Demand for LPVs has increased as a result of environmental regulations of international organizations. However, scant research exists on the analysis of LNG bunkering ports.

(2) Related LNG bunkering industries are still in an early phase and technologies are new. These industries will most likely develop and offer even more sustainable alternatives for the future.

(3) Advanced ports (Singapore, Rotterdam) are already preparing for LNG bunkering. The government or PA preparing the LNG bunkering port will be able to implement policies for more competitive LNG ports by understanding the priorities of shipping companies when selecting LNG bunkering ports.

The composition of the analysis is as follow.

<insert Figure 2 around here>

Phase 1. Identification of criteria for LNG bunkering port selection

As previously mentioned, through expert interviews and the literature review, 20 sub-criteria for five main criteria were identified. See Table 2 for details.

Phase 2. Rank the criteria using fuzzy-AHP

Respondents were asked to construct pairwise comparisons of the five major criteria and 20 sub-criteria by employing linguistic variables. Using the arithmetic mean, the pairwise comparison matrices of the criteria and sub-criteria are established. The results from the computations using the pairwise comparison matrices are shown in Tables 9 and 10. The consistency ratio values of all matrices are less than 0.1, indicating that these matrices are sufficiently consistent. Then, linguistic expressions were transformed into FTNs and a fuzzy evaluation matrix was established (see Table 1). The next step is to obtain a fuzzy weighted evaluation matrix. Using the criteria weight calculated, the weighted evaluation matrix is established by Eq. (3) and Eq. (4). The results of the analysis are shown in Tables 3–10.

<insert Table 5-12 around here>

5. Discussion and concluding remarks

Studies on LNG bunkering port selection that incorporate applications from the perspective of shipping companies are lacking. This paper offers invaluable policy implications for governments and PAs that plan to build and operate LNG bunkering ports in the near future. The results of the analysis enable them to: (1) more clearly understand the needs of shipping companies regarding LNG bunkering ports, (2) determine how to provide efficient LNG bunkering services, and (3) make prompt adjustments to meet their development strategies. The results also enable LNG bunkering port managers to: (1) grasp the present strengths and weaknesses of their ports and (2) help them establish future strategies to improve the competitiveness of their ports. This paper represents a first step in exploring LNG bunkering port selection.

The final ranking of the criteria is determined according to the BNP values. The results indicate that, among the 20 sub-criteria of LNG bunkering port selection by shipping companies, geographical location (G1) ranked first as the most competitive factor, followed by LNG bunkering safety (SS1), port traffic (G3), and port accessibility (G2). In reality, shipping companies normally obtain LNG bunkering services at the North Sea and the Baltic Sea given the ECAs. In addition, in these regions, LPVs are actively being operated and LNG bunkering ports are the most distributed. These examples might indicate that the adoption of an ECA is highly related to the development of LNG bunkering ports. Moreover, for shipping companies to make optimal decisions on the choice of LNG bunkering ports may be helpful. After the analysis, the strategic recommendations may be provided to the government or PA that is preparing the LNG bunkering port. The results indicate that most shipping companies decide on a LNG bunkering port with a stronger emphasis on safety/security or port services rather than port reputation. Therefore, when developing a LNG bunkering port, the government and the PA should improve its safety and security under limited port capacity to enhance its LNG bunker supply efficiency and shorten its waiting time. Meanwhile, the findings indicate that the efficiency of the LNG bunkering process (PS1) was a considerable factor. Therefore, port operators should improve the efficiency of port operations and, at the same time, secure sound LNG bunker suppliers in the port. Such partnerships will lead more shipping companies to obtain LNG bunker services at this port by reducing ship turnaround time (Barnes-Dabban, va Tatenhove, and van Koppen 2017).

One of interviewees argued that “IMO's lowering of sulfur content from 3.5% to 0.5% should eventually mean not to use fossil fuels. Therefore, considering the ship's life span is 30 years, it is important to pay attention to what will be the regulations after 2025 and to build know-how by trying various methods such as LNG fuel.” Another interviewee mentioned that "The desirable direction of LNG-powered vessels is to promote shipbuilding orders, and it is necessary to apply more than mid-sized public shipbuilding orders as LNG-propelled vessels. Therefore, it is necessary to gradually expand the infrastructure facilities that can supply LNG as ship fuel, and to support cooperation between international ports between the governments."

The Korean government is organizing the 'LNG Propulsion Shipbuilding Industry Association' in cooperation with shipbuilding, shipping, and port, and is conducting a pilot project. The Korean government of is supporting POSCO's pilot project to introduce the 180,000-ton LPV. Currently, eight organizations are cooperating, including the Ministry of Maritime Affairs and Fisheries, the Ministry of Industry and Commerce, POSCO, the Korea

Gas Corporation, the Korean Register, the Korea Development Bank, the LNG Bunkering Industry Association and the Shipbuilding, and Marine Plant Research Institute (Chosun Biz 2017).

In light of these interviews and government policies, we recommend the following policies, taking into account both the earlier theoretical assessments and empirical evidence.• Incentive/discount policy: The incentive and discount policy is a significant problem arising from the introduction of LPVs. The government and the PA should use various forms of financial support to promote LNG bunkering in its port, such as by developing a differential port tariff for LPVs, such as the Green Award at the port of Rotterdam and the Environmental Ship Index (ESI) of WPCI.

• Communication policy: The government and the PA should take a conative coordinating role with respect to sustaining honourable communication within the port community regarding the its LNG bunkering port, such as by (a) improving public opinion to promote the use of LNG bunkering ports and (b) projecting a publicity campaign or by forming conferences, seminars, or workshops (Lun 2011).

• Collaborative policy: The government or the PA preparing a LNG bunkering port should institute collaboration opportunities with stakeholders of the port (e.g., industrial players such as LNG bunkering ports, LNG suppliers, and port users). Collaboration can focus on the development of the LNG port (e.g., location selection), the safety assessment of the LNG port environment, and the development of bunkering standards and guidelines. Collaboration is believed to improve interactive knowledge and its sharing, which can reduce market uncertainty (Wang and Notteboom 2015).

The following items highlight the study’s limitations: (1) because no major LNG bunkering ports exist, shipping companies have limited selection; (2) for the same reason, this study cannot propose alternative LNG bunkering ports; and (3) shipping companies′ decisions may be non-objective and may neglect actual vessel and port conditions. Therefore, important additional studies can follow this paper. Future research directions are as follows: (1) shipping companies that lack LPVs should be added to the analysis; (2) after large LNG bunkering ports are constructed, alternatives should be analyzed; and (3) a two-phase methodology combining fuzzy-AHP-TOPSIS and a sensitivity analysis can be incorporated to confirm the robustness of the analysis. Finally, a stated preference approach could have been selected and governments/PA should have been interviewed or have data collected from them in terms of how they would like to further develop LNG bunkering facilities in details. Nevertheless, the authors strongly believe that the study has provided an ideal platform for further research on this increasingly important subject.

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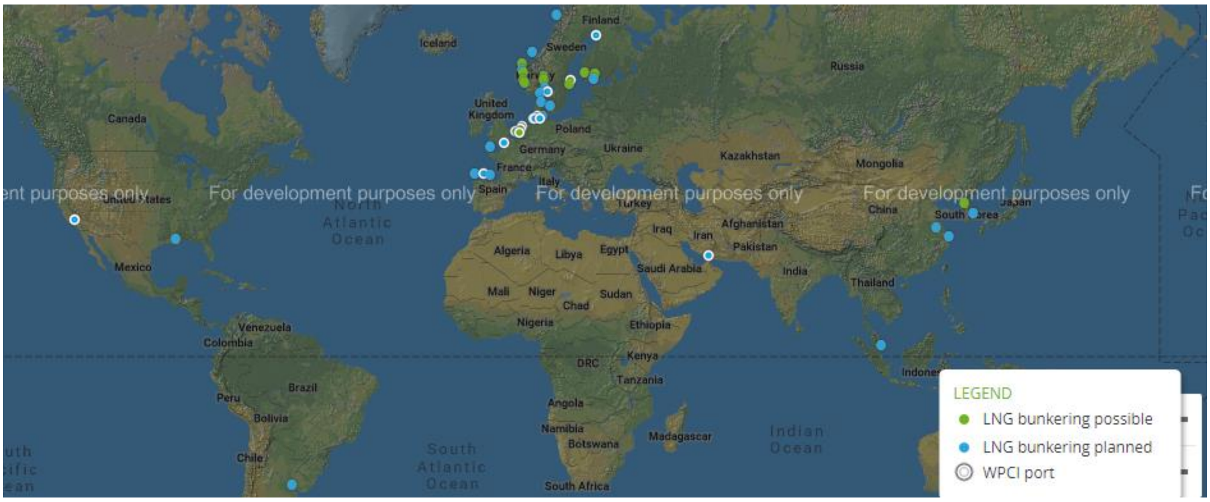

Figure 1. LNG bunkering possible and planed ports in the world (Source: WPCI website)

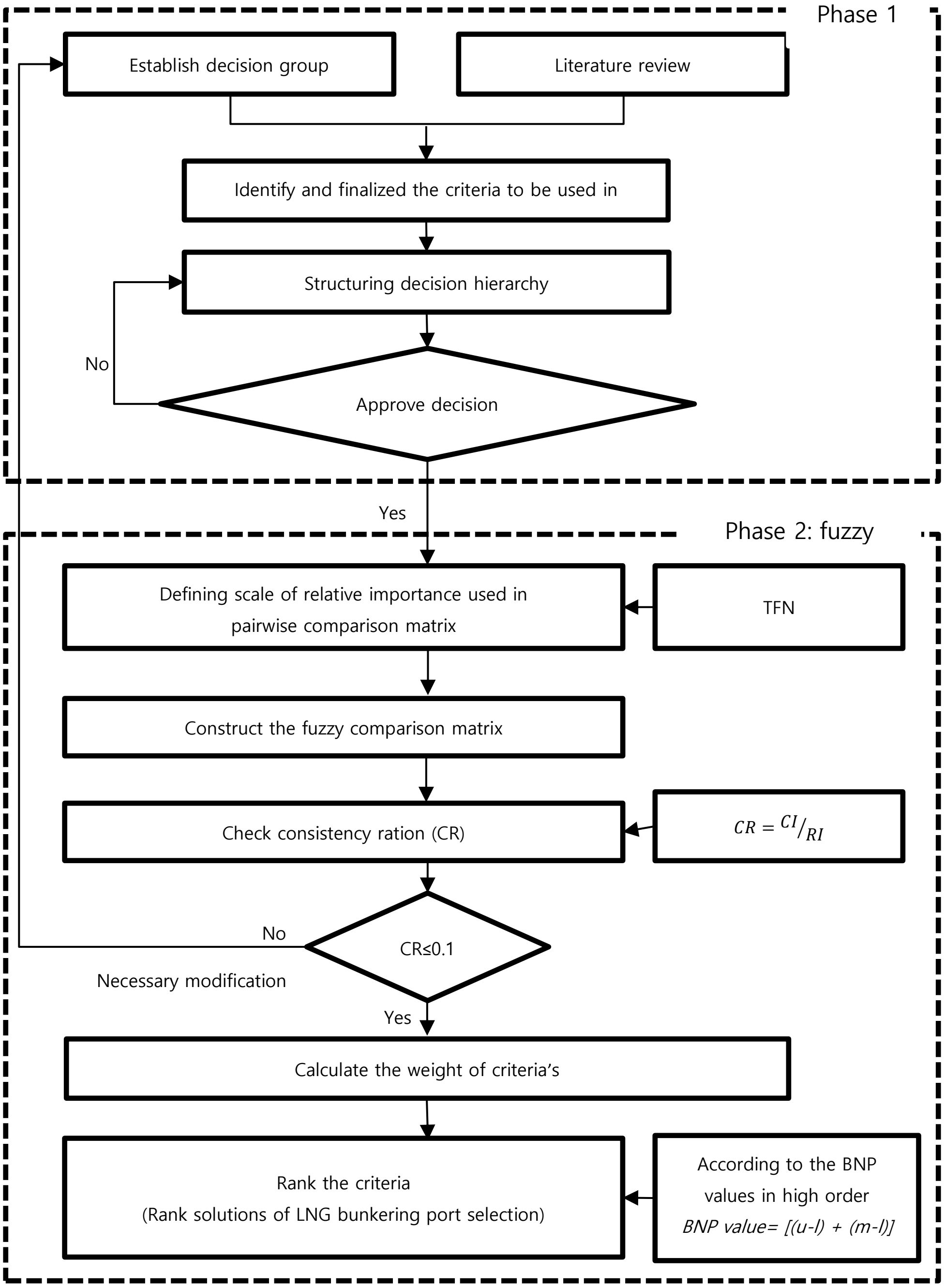

Figure 2. The methodology of two main stages

Table 1. Literature on the main factors that determine port selection

Factors	References
Infrastructure	Ugboma, Ugboma, and Ogwude 2006; Tiwari, Itoh, and Doi 2003
Geographic location	Chang, Lee, and Tongzon 2008; Saeed 2009
Costs	Ugboma, Ugboma, and Ogwude 2006; Saeed 2009
Quality of port services	Tongzon 2009; Lirn et al. 2004

Table 2. Literature on the main factors that determine LNG bunkering port

Factors	References
LNG bunkering safety	DNV 2012; ABS 2015; IACS 2016
Price of LNG fuel	Lloyd's Register 2012; 2014; ABS 2015; Tetraplan 2014
Port location	Lloyd's Register 2012; 2014; Tetraplan 2014
Technologies for LNG bunkering	DNV 2012; ABS 2015

Table 3. Membership function of linguistic scale

Fuzzy number	Linguistic term	Scale of fuzzy number
1	Equal	(1, 1, 1)
2	Weak advantage	(1, 2, 3)
3	Not bad	(2, 3, 4)
4	Preferable	(3, 4, 5)
5	Good	(4, 5, 6)
6	Fairly good	(5, 6, 7)
7	Very good	(6, 7, 8)
8	Absolute	(7, 8, 9)
9	Perfect	(8, 9, 10)

Table 4. The criteria and their descriptions

Main criteria	Sub-criteria	Description
Cost (M1)	Incentive/discount (C1)	Discounts and incentives on eco-friendly vessels from environmental regulations of international organizations (Danish Maritime Authority 2012; Wang and Notteboom 2015; Port of Gothenburg 2017)
	LNG price (C2)	Low LNG price (Register 2012; ABS 2015; Wang and Notteboom 2015; Tetraplan 2014)
	Port service charge (C3)	Low port service charge (Tongzon 2009; Hesse and Rodrigue, 2004; Gohomene, Bonsal, and Maistralis 2016)
	Ship turnaround time (C4)	Short ship turnaround time attributable to saving operating costs (Saeed, 2009; Nir, Lin, and Liang 2003; Bird 1988)
Geography (M2)	Geographical location (G1)	Proximity to ECAs or main navigation routes (Tetraplan 2014; Ng 2006; SSPA 2017)
	Port accessibility (G2)	Closeness to shipping companies' service routes (Acosta, Coronado, and Cerban 2011; Wang, Yeo, and Ng 2014)
	Port traffic (G3)	Number of calls at port (Tiwari, Itoh, and Doi 2003; Lirn, Thanopoulou, and Beresford 2003; Tetraplan, 2014)
	Port weather conditions (G4)	Sound weather conditions for LNG bunkering (Notteboom and Vernimmen 2009)
Port reputation (M3)	Experienced human resources (PR1)	Education and training requirement for workers of the bunker vessel and experienced workers at the port (Lloyd's Register 2014; Danish Maritime Authority 2012; SSPA 2017)
	Port disputes (PR2)	Low level of port disputes (Acosta, Coronado, and Cerban 2011)
	Public opinion/word of mouth (PR3)	Retain/develop positive public perception of the port (Tongzo, 2009; Ugboma, Ugboma, and Ogwude 2006; Ng, 2006)
	Technical conditions related to LNG bunkering (PR4)	Required facilities and technology for LNG bunkering (e.g., TTS: Truck-to-ship, STS: Ship-to-ship, TPS: Terminal-to-ship) (DNV 2012; ABS 2015; ASCS 2016; Danish Maritime Authority 2012)
Port service (M4)	Efficiency of LNG bunkering process (PS1)	Short bunkering time attributable to the efficiency of the LNG bunkering process (ASCS 2016; Wang and Notteboom 2015; Port of Gothenburg, 2017)
	Infrastructure /superstructure (PS2)	Infrastructure and facilities provision for LNG bunkering (Port of Gothenburg 2017; ABS 2014; Port of Antwerp 2015; Wang and Meng 2012)
	Port congestion (PS3)	Low port congestion (Lloyd's Register 2012; 2014; Tetraplan 2014)
	Relationship among stakeholders (PS4)	Sound relationship among LNG ports, LNG suppliers, and port users (Chang, Lee, and Tongzon 2008; Saeed, 2009; Ng, 2006)
Safety /security (M5)	LNG bunkering safety (SS1)	LNG bunkering safety (e.g., ESD; Emergency Shut-down Systems, Safeguard Systems) (Lirn et al. 2004; IACS 2016; ABS 2015; Trbojevic and Carr 2000)
	Port security (SS2)	Number of accidents, accidents prevented, and guards (Bichou 2008; Bajpai and Gupta 2007; SSPA 2017)

LNG bunkering regulations (SS3)	Compliance with regulations and standards for LNG bunkering, such as regulations of SIGTTO (Society of International Gas Tankers and Terminal Operators), OCIMF (Oil Companies International Marine Forum), IMO (International Maritime Organization), ISO (International Organization for Standardization), CEN (European Committee for Standardization), and NFPA (National Fire Protection Association) (Lloyd's Register 2012; DNV 2012; ABS 2014; Port of Gothenburg 2017; SSPA 2017)
LNG supply regulations (SS4)	Compliance with regulations and standards for LNG supply, such as ISO.TS 18683:2015 Guidelines for Systems and Installations for Supply of LNG as Fuel to Ships, LNG Bunker Checklists developed by IAPH's (International Association of Ports and Harbors) WPCI (World Ports Climate Initiative) (Lloyd's Register 2014; ABS 2015; Danish Maritime Authority 2012; Wang and Notteboom 2015; Ng 2006)

Table 5. Fuzzy comparison matrix of the major criterion

	M1	M2	M3	M4	M5
M1	(1, 1, 1)	(0.523, 0.543, 0.566)	(1.431, 1.550, 1.650)	(0.699, 0.780, 0.933)	(0.552, 0.577, 0.608)
M2	(1.765, 1.841, 1.911)	(1, 1, 1)	(1.813, 1.885, 1.951)	(1.578, 1.676, 1.762)	(1.116, 1.231, 1.311)
M3	(0.606, 0.645, 0.699)	(0.512, 0.530, 0.552)	(1, 1, 1)	(0.550, 0.575, 0.606)	(0.506, 0.523, 0.543)
M4	(1.072, 1.282, 1.431)	(0.568, 0.597, 0.634)	(1.650, 1.738, 1.817)	(1, 1, 1)	(0.608, 0.649, 0.707)
M5	(1.644, 1.733, 1.813)	(0.763, 0.812, 0.896)	(1.841, 1.911, 1.974)	(1.414, 1.540, 1.644)	(1, 1, 1)

Table 6. Fuzzy comparison matrix of the cost criterion

	C1	C2	C3	C4
C1	(1, 1, 1)	(1.234, 1.390, 1.516)	(1.072, 1.282, 1.431)	(1.149, 1.246, 1.320)
C2	(0.660, 0.719, 0.812)	(1, 1, 1)	(0.660, 0.719, 0.812)	(1.072, 1.116, 1.149)
C3	(0.699, 0.780, 0.933)	(1.231, 1.390, 1.516)	(1, 1, 1)	(1.116, 1.231, 1.311)
C4	(0.758, 0.803, 0.871)	(0.871, 0.896, 0.933)	(0.763, 0.812, 0.896)	(1, 1, 1)

Table 7. Fuzzy comparison matrix of the geography criterion

	G1	G2	G3	G4
G1	(1, 1, 1)	(1.718, 1.801, 1.876)	(1.789, 1.863, 1.931)	(1.841, 1.911, 1.974)
G2	(0.533, 0.555, 0.582)	(1, 1, 1)	(0.836, 0.933, 0.072)	(1.374, 1.506, 1.614)
G3	(0.518, 0.537, 0.559)	(0.933, 1.072, 1.196)	(1, 1, 1)	(1.231, 1.105, 1.534)
G4	(0.506, 0.523, 0.543)	(0.620, 0.664, 0.728)	(0.652, 0.712, 0.812)	(1, 1, 1)

Table 8. Fuzzy comparison matrix of the port reputation criterion.

	PR1	PR2	PR3	PR4
PR1	(1, 1, 1)	(1.707, 1.789, 1.863)	(1.733, 1.813, 1.885)	(1.149, 1.335, 1.473)
PR2	(0.37, 0.559, 0.586)	(1, 1, 1)	(1.320, 1.463, 1.578)	(0.568, 0.610, 0.634)
PR3	(0.530, 0.552, 0.577)	(0.634, 0.683, 0.758)	(1, 1, 1)	(0.547, 0.584, 0.602)
PR4	(0.679, 0.749, 0.871)	(1.578, 1.639, 1.762)	(0.661, 1.712, 1.829)	(1, 1, 1)

Table 9. Fuzzy comparison matrix of the port service criterion.

	PS1	PS2	PS3	PS4
PS1	(1, 1, 1)	(1.231, 1.390, 1.516)	(1.639, 1.730, 1.810)	(0.777, 0.846, 0.922)
PS2	(0.660, 0.719, 0.812)	(1, 1, 1)	(1.414, 1.540, 1.644)	(0.634, 0.683, 0.758)
PS3	(0.552, 0.578, 0.610)	(0.608, 0.649, 0.707)	(1, 1, 1)	(0.512, 0.530, 0.550)
PS4	(1.084, 1.182, 1.096)	(1.320, 1.463, 1.578)	(1.817, 1.888, 1.954)	(1, 1, 1)

Table 10. Fuzzy comparison matrix of the safety/security criterion.

	SS1	SS2	SS3	SS4
SS1	(1, 1, 1)	(1.453, 1.578, 1.681)	(1.603, 1.699, 1.783)	(1.614, 1.712, 1.796)
SS2	(0.595, 0.634, 0.688)	(1, 1, 1)	(0.912, 1.041, 1.149)	(0.922, 1.023, 1.196)
SS3	(0.561, 0.589, 0.624)	(0.871, 0.960, 1.096)	(1, 1, 1)	(1.010, 1.041, 1.088)
SS4	(0.557, 0.584, 0.692)	(0.836, 0.978, 1.084)	(0.919, 0.960, 1.001)	(1, 1, 1)

Table 11. Ranking of main criteria for LNG bunkering selection.

Major criterion	Consistency	Major criterion weight	Major criterion BNP	Ranking
Cost (M1)		(0.142, 0.157, 0.177)	0.159	4
Geography (M2)		(0.257, 0.283, 0.309)	0.283	1
Port reputation (M3)	0.091	(0.111, 0.121, 0.133)	0.122	5
Port service (M4)		(0.165, 0.185, 0.207)	0.186	3
Safety/security (M5)		(0.230, 0.254, 0.280)	0.255	2

Table 12. Ranking of sub-criteria and total ranking for LNG bunkering selection

Sub-criterion	Consistency	Local			Normalized	
		Sub-criterion weight	BNP	Ranking	BNP	Ranking
C1	0.066	(0.257, 0.302, 0.345)	0.301	1	0.048	11
C2		(0.191, 0.216, 0.248)	0.218	4	0.035	17
C3		(0.229, 0.266, 0.310)	0.268	2	0.043	12
C4		(0.195, 0.216, 0.245)	0.219	3	0.035	16
G1	0.088	(0.351, 0.380, 0.411)	0.381	1	0.108	1
G2		(0.201, 0.227, 0.252)	0.226	3	0.064	4
G3		(0.200, 0.228, 0.253)	0.226	2	0.064	3
G4		(0.153, 0.169, 0.189)	0.170	4	0.048	10
PR1	0.094	(0.309, 0.346, 0.380)	0.345	1	0.042	14
PR2		(0.181, 0.201, 0.221)	0.201	3	0.025	19
PR3		(0.149, 0.164, 0.181)	0.165	4	0.020	20
PR4		(0.263, 0.289, 0.327)	0.293	2	0.036	15
PS1	0.096	(0.259, 0.289, 0.323)	0.290	2	0.054	9
PS2		(0.203, 0.225, 0.257)	0.228	3	0.042	13
PS3		(0.149, 0.161, 0.179)	0.163	4	0.030	18
PS4		(0.294, 0.325, 0.347)	0.322	1	0.060	5
SS1	0.090	(0.319, 0.356, 0.393)	0.356	1	0.091	2
SS2		(0.193, 0.221, 0.254)	0.223	4	0.057	6
SS3		(0.191, 0.213, 0.239)	0.215	3	0.055	7
SS4		(0.185, 0.210, 0.240)	0.212	2	0.054	8