An improved formal safety assessment methodology with Fuzzy TOPSIS for developed LPG fueled marine engine system

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Abbreviations

ABS	American bureau of shipping
ALARP	As low as reasonably practicable
CAN	Controller area network
CCC	Carriage of cargoes
ECS	Engine control system
ECU	Electric control unit
EGR	Exhaust gas recirculation
ETA	Event tree analysis
FMEA	Failure mode and effect
FNIS	Fuzzy negative ideal solution
FPIS	Fuzzy positive ideal solution
FSA	Formal safety assessment
GCAF	Gross cost of averting a fatality
HFO	Heavy fuel oil
HAZOP	Hazard and operability analysis
IACS	International association of classification society
IMO	International Maritime Organization
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
MCDM	Multi criteria decision making
MODU	Mobile offshore drilling units
NCAF	Net cost of averting a fatality
NPV	Net present value
PDT	Pressure differential transmitter
PLL	Potential loss of life
PMS	Power management system
RCM	Risk control measures
RCO	Risk control option
TOPSIS	Technique for order performance by similarity to ideal solution

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Abstract

In this study, a risk assessment of a Liquefied petroleum gas (LPG) marine engine system being developed for installation in the first LPG-powered ship in South Korea was performed and a new standard for a formal safety assessment (FSA) was proposed. Based on the FSA technique, hazards were identified through a failure mode and effect analysis (FMEA) in the first stage. An FMEA workshop was conducted to assess 110 components, and 89 hazards were identified. Of these, 19 failure modes of intolerable level were identified, and risk ranks were divided into four groups. Then, a more objective risk assessment was conducted using fuzzy set theory to compensate for the subjectivity of FMEA. Additionally, a technique for order performance by similarity to ideal solution (TOPSIS) was used to represent the risk rank of individual systems more precisely. By the second stage, risk ranks could be divided into 28 groups by classifying a total of 89 hazards. Finally, risk control options were presented for high-ranking hazards according to the fuzzy TOPSIS results, and a cost-benefit analysis was performed. Consequently, the gross and net costs of averting a fatality were calculated as US $2.98 million and US $2.93 million, respectively. Through a cost-benefit analysis, the periodic exchange of main critical components was found to be in the range of economic criteria that could be recommended as a safety standard. The risk assessment technique proposed in this study allows a more objective and effective selection of critical hazards that necessitate risk control measures.

Keywords: LPG marine engine, Risk assessment, Formal safety assessment, Failure mode and effect analysis , Fuzzy logic, TOPSIS

1. Introduction

Today, more than 80–90% of global trade is conducted via sea transportation that plays a crucial role in international trade (Walker et al., 2019). As of end 2019, the world trade increased by 18% relative to that in 2016 (WTO, 2021). As of 2018, greenhouse gases (GHG) and carbon dioxide (CO_2), the major pollutants emitted from ships, exceeded 1,000 million tons and increased by 9.6% and 9.3% relative to those in 2012, respectively (IMO, 2020). With the escalating requirement of the reduction of greenhouse gas emissions in the shipping sector, the International Maritime Organization (IMO) has set a strategy to reduce CO_2 emissions by 70% relative to that in 2008 by 2050 and to reduce the total annual GHG emissions by at least 50% by 2050

(IMO, 2018a).

In order to reduce pollutants generated by ships, the use of alternative fuels such as liquefied natural gas (LNG) and liquefied petroleum gas (LPG) instead of the conventionally used heavy fuel oil (HFO) is widely recognized as a viable solution in the medium to long term (Xing et al., 2021). Recently, there has been a growing interest in R&D on non-carbon fuels such as ammonia and hydrogen fuels as well as biofuels for the long-term complete decarbonization of shipping (Ampah et al., 2021). Among the alternative fuels, particularly LPG fuel can reduce air pollutants with comparable effectiveness as LNG; furthermore, the annual fuel consumption and fuel consumption cost of LPG fuel are comparable to those of HFO that is conventionally used. There are also many advantages such as ease of fuel storage and transportation, abundant supply infrastructure, and wide application regardless of the size of ships. However, LPG fuel is associated with risk owing to its inherent characteristics. Furthermore, there are not many reports of the LPG fuel-based operation of a ship propulsion system in small and medium-sized ships in particular, and the safety regulations applicable to the system are insufficient (Yeo et al., 2022).

Meanwhile, in South Korea, the LPG engine power generation hybrid electric propulsion ship is under construction to enable the application of the eco-friendly and economical LPG fuel in small and medium-sized ships (<400 tons with <2000 kW output) with a high possibility of conversion to LPG fuel that account for >91% of domestic registered ships. Considering the insufficient safety regulations of the newly developed LPG marine engine system, a risk-based approach must be adopted from the beginning of the basic design process. Furthermore, a more objective and rational risk assessment is required for the identification of important safety problems and development of improvement measures necessary for safety improvement (Cao et al., 2022; Monzingo, 2020).

Among the risk assessment tools, the failure mode and effect analysis (FMEA) is a technique used in various industrial fields for the improvement of the security and reliability of systems in a simple and efficient manner (Lo and Liou, 2018; Wang et al., 2018). In the shipping industry, detailed FMEA guidelines for application to mobile offshore drilling units (MODU), offshore support vessels, steel vessels, and high-speed craft have been established (American Bureau of Shipping, 2015). FMEA uses the assessment of the risk factors of FMEA team members to identify each failure mode, and the risks of the identified failure modes can be ranked in order of importance (IEC, 2018). In the evaluation process, various uncertainties including inaccuracy, ambiguity, and incompleteness are presented in the subjective evaluation of team members owing to limited knowledge and professionalism (Chen and Deng, 2018).

In order to address the uncertainty of risk analysis, research has been conducted in various academic fields. The fuzzy set theory is one of the methods employed to solve uncertainties in the application of engineering technology (Abdussamie et al., 2018; Ahn and Chang, 2016). Fuzzy theory can quantify the ambiguity and uncertainty of linguistic variables by considering approximate or subjective numbers; this is advantageous in minimizing information loss by simplifying complex phenomena (Dubois and Prade, 2012; Ross, 2005). Efe (2019) collected expert opinions based on linguistic terms and transformed them into intuitionistic fuzzy numbers to overcome the limitations of traditional FMEA. Siswantoro et al. (2020) determined the facility maintenance priorities based on the fuzzy FMEA analysis to complement the subjective evaluation of the FMEA for the cooling water system of a marine diesel engine (~4000 kW). Fuzzy theory is adopted by incorporating not only FMEA, but also various risk assessment tools. In the fuzzy fault tree analysis technique, fuzzy theory is used to convert the failure rate of basic events into fuzzy numbers due to the uncertainty of failure data. (Cheliyan and Bhattacharyya, 2018; Zhang et al., 2021). In order to compensate for the shortcomings of the hazard and operability analysis (HAZOP), Cheraghi et al. (2019) proved that the fuzzy HAZOP could provide a more transparent and detailed risk rankings compared with the traditional HAZOP in operating gas wellhead facilities, thereby enabling effective safety management.

According to Liu et al. (2013), the techniques proposed to overcome the shortcomings of FMEA also included the multi-criteria decision making (MCDM) method. MCDM method is the process of selecting an optimal alternative as a rational decision-making method by considering several different attributes or criteria (Dehshiri, 2022). Various MCDM methods have been applied to most fields in the industry (Li and Hu, 2021).

Among them, the technique for order performance by similarity to ideal solution (TOPSIS) is a rational method that considers the best and worst alternatives simultaneously and compares and evaluates alternatives from the perspective of various attributes. In particular, fuzzy TOPSIS is one of the techniques used under uncertainty, particularly when there are a large number of alternatives to be considered (Grassi et al., 2009). Asupuo et al. (2019) applied the fuzzy TOPSIS technique to rank suitable maintenance methods for onboard machinery (cranes) for ships operating in uncertain environments. Kolios et al. (2017) proposed the fuzzy TOPSIS method to analyze the failure mode of the subsea control module identified through FMEA and to assess the most important risks. It was suggested as a technique that could be applied more practically to various systems. Rani et al. (2020) applied the fuzzy TOPSIS technique in selecting a renewable energy source that has recently emerged as an important issue in environmental development.

In the shipping industry, the formal safety assessment (FSA) method approved by IMO is used for risk assessment and the establishment of safety regulations (IMO, 2018b). The FSA technique has been primarily developed to address the need for a development procedure of a more systematic and reliable safety regulation incorporating risk-reduction measures and cost-benefit analysis in the decision-making process, based on the aforementioned risk assessments such as FMEA and HAZOP.

Endrina et al. (2018) applied the FSA technique for risk analysis based on accident statistics of roll on/roll off passenger ships operating in the Strait of Gibraltar, where 110,000 ships travel annually. Wang et al. (2020) identified hazards using the hazard identification (HAZID) technique for a high-speed battery powered ferry that operates in a number of small islands for passenger transportation in the Norwegian Sea. Through cost-benefit analysis of the suggested risk control option (RCO) for the reduction of accidents, changing the battery room installation location was found to be the most cost-effective method. For reference, in this study, hazards were identified through HAZID, a qualitative risk evaluation technique, and the subjectivity of evaluation was supplemented through quantitative evaluation techniques such as the event tree analysis (ETA) and fault tree analysis (FTA) for risk evaluation. However, it requires extensive time and manpower to perform the entire FSA (IMO, 2007a).

Therefore, this study aims to improve the efficiency of risk assessment by formulating risk assessment and safety standards for the 200-kW class LPG engine currently being developed in South Korea by applying the fuzzy TOPSIS-based FMEA via the FSA method, where the fuzzy set theory compensates for the uncertainty of FMEA (Ahn and Chang, 2016); TOPSIS is used in a fuzzy environment to represent the risk rank of individual systems more precisely (Cheraghi et al., 2019; Jeong et al., 2019; Kolios et al., 2017). An RCO is prepared through this to reduce the probability of damage to the LPG marine engine system for items with a high risk among hazards classified more precisely or to reduce the severity of the consequences of an accident. In addition, a cost-benefit analysis is conducted to ensure the reliability of the RCO, followed by an evaluation of the cost-effectiveness of the proposed RCO.

This paper is structured as follows. Section 2 describes the main specifications and technical details of the LPG marine engine system, the subject of risk assessment. Section 3 describes the research method used in this study. Section 4 describes the results of applying the techniques used in this study in detail, followed by Section 5 that presents the importance and possibility of the techniques applied in this study. Section 6 presents the conclusions of this study.

2. System description

To commercialize the LPG propulsion system for small and medium-sized ships, the first LPG-fueled ship building project is underway in South Korea; it is essentially a ship with an LPG engine-powered hybrid electric propulsion system. The propulsion system to be installed on the 24-m-long government ship (fishery supervision vessel) will be equipped with two LPG engine generators and two batteries as propulsion power sources to enable the safe operation of the ship, toward the development of the first LPG engine in South Korea. The power generated by the LPG engine generator drives the propulsion motor to rotate the propeller of the ship, while the battery is used as an emergency power source.

The LPG engine specifications are shown in Table 1. The engine is a modified land-compressed natural gas (CNG) engine. To convert a CNG to an LPG engine, changes in the cylinder unit according to the change in compression ratio, replacement of the fuel supply for liquid LPG fuel injection (the CNG engine involves gaseous fuel injection), and application of a seawater cooling system considering marine engines are required.

Table 1 Design specification of LPG marine generator.

Engine power	210 kW @ 1,800rpm
Engine Type	In-Line type 4 Cycle Water Cooled, Turbo charged & Intercooled (Air to Water)
Combustion type	Stoichiometric Combustion, Spark Ignition
Number of Cylinders	6
Bore × stroke	133 × 140 mm
Displacement	11,670 cc
Compression ratio	9.5 : 1

In this study, risk assessment was performed on the LPG engine control system comprising the fuel supply system as shown in Fig. 1 and the electric control system. The LPG fuel supply is injected into the engine in a liquid state at a static pressure of 20 bar, and the main component of LPG is propane (100%).

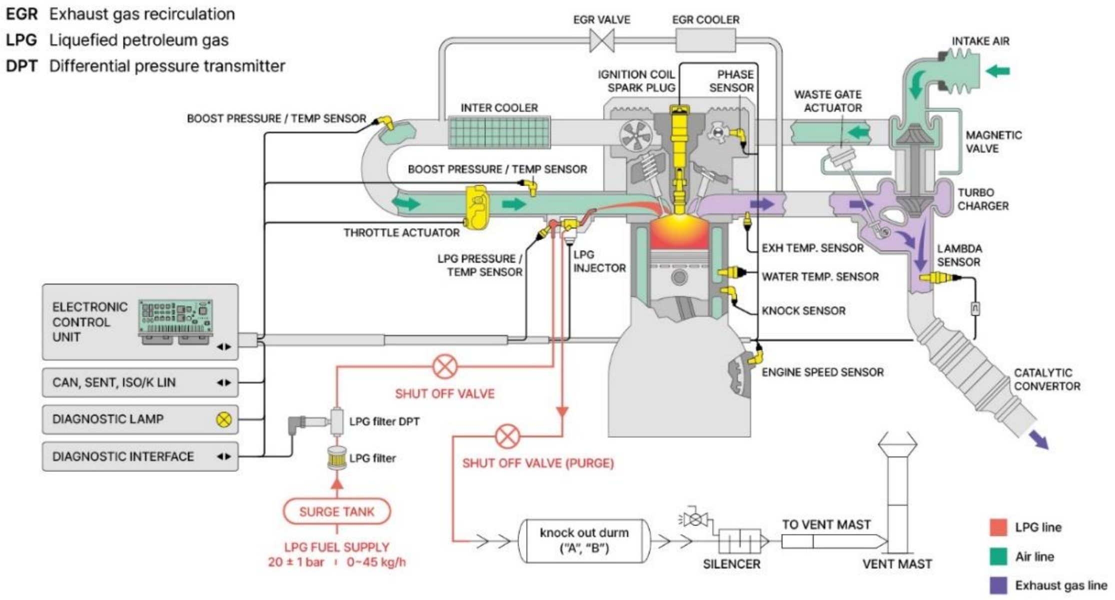


Fig. 1. Schematic of fuel supply system of LPG fuel marine engine.

The developed LPG fuel marine engine has a Lambda sensor installed on the exhaust gas outlet side for operation at a stoichiometric air–fuel ratio by controlling the amount of fuel based on the measurement of the oxygen concentration in the exhaust gas. In addition, the three-way catalyst purifies the nitrogen oxides in the exhaust gas emitted from LPG combustion through the catalytic converter. A knock sensor has been installed to detect knocks caused by abnormal combustion during engine operation. When a knock is detected, the ignition timing is changed to move to an area where the knock does not occur, thereby reducing the output and protecting the engine. Furthermore, a knock out drum (KOD) is installed on the vent mast side to prevent the LPG fuel from directly leaking into the liquid state during the purging process while supplying liquid LPG fuel to the engine, as a distinguishing feature from other dual fuel systems using gaseous fuel. For the electric control system, engine control is performed by the engine control system (ECS). Upon receiving the data from the sensors measured by the engine through CAN communication with a value greater than the standard value, the engine generator controller side features a function to stop the engine by sending it to the power management system (PMS).

3. Method

In the fuzzy TOPSIS FMEA, detectability was incorporated in the existing FMEA considering two risk factors, and four experts were selected to derive weights for three risk factors for each expert. After identifying the hazards and their respective hazard indices, the TOPSIS technique was used to prioritize and specifically determine their risk ranks. In order to cope with the uncertainty of expert opinions, weights for risk factors and TOPSIS were combined with fuzzy logic. Based on the TOPSIS results, RCOs were identified for hazards with a high-risk rank, and safety standards were proposed through cost-benefit analysis. Fig. 2 shows the steps for FMEA, fuzzy TOPSIS FMEA, and FSA that will be explained in more detail in the next section.

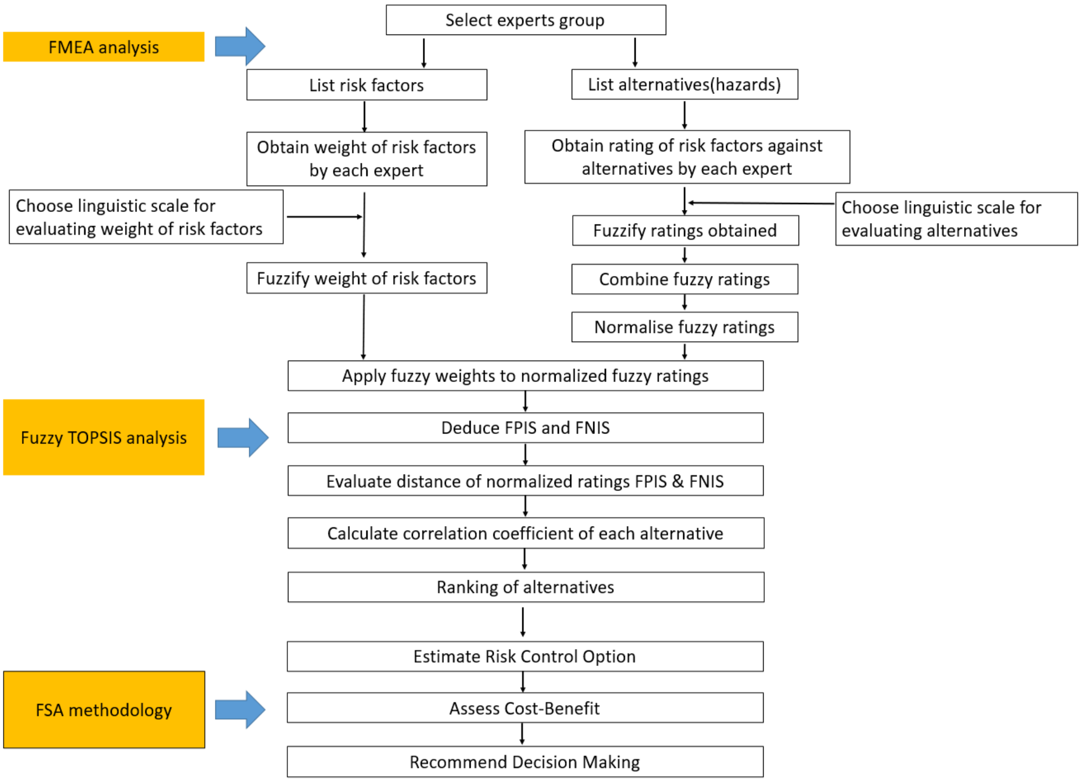


Fig. 2. FSA methodology with fuzzy TOPSIS FMEA on LPG marine engine system.

3.1. FMEA analysis

3.1.1. Application of FMEA analysis to the LPG marine engine system

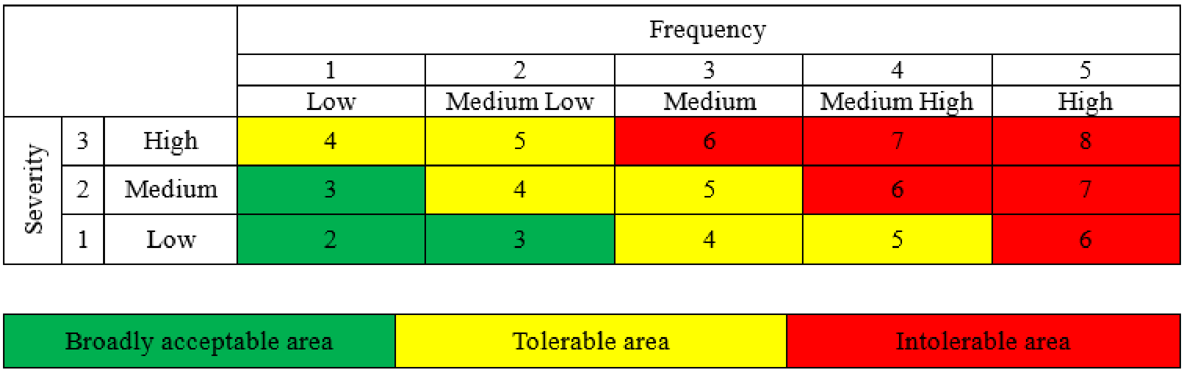
The FMEA for LPG engine control systems is aimed at providing a comprehensive, systematic, and documented analysis for the identification of failure modes for each component of the system and the analysis of their effects in relation to the acceptable safety and performance criteria. Risk assessment was performed according to international standards (IEC, 2018), and the FMEA of the LPG engine control system was performed as the system FMEA (IACS, 2014). System FMEA was implemented in a top-down approach, starting at the overall system level and progressing to the next subsystem level or component level. In this study, FMEA determined the risk ranks based on a qualitative evaluation of the frequency (Table 2) and the severity of results (Table 3) applied to engine control systems in accordance with the International Association of Classification Society (IACS) recommendation 138 and the American Bureau of Shipping (ABS) Classification guidelines using a corresponding risk matrix (Fig. 3). The risk matrix can be divided into three areas. The broadly acceptable area (here, the lower left area with indices 2 and 3), the intolerable area (here, the upper right area with indices 6, 7, and 8), and the area between the two aforementioned areas (here, the diagonal area with indices 4 and 5). This is the tolerable area that is the as low as reasonably practicable (ALARP) risk area, based on the principle of practical and reasonable minimization, and the risk level of the related risks or component failure can be regarded as an acceptable level.

Table 2 Frequency index for FMEA (ABS, 2016).

Index	Description	Definition
1	Low	Less than 1 event in 1,000 engines per year of engine operation
2	Medium Low	1 event in 1,000 to less than 1 event in 100 engines per year of engine operation
3	Medium	1 event in 100 to less than 1 event in 10 engines per year of engine operation
4	Medium High	1 event in 10 to less than 1 event in 1 engine per year of engine operation
5	High	1 or more events per year of engine operation

Table 3 Severity index for FMEA (IACS, 2014).

Index	Description	Definition
1	Low	Negligible to low impact on safety and/or Negligible to low impact on engine performance
2	Medium	Medium impact on safety, e.g., injury and/or Medium impact on engine performance e.g., engine de-rated
3	High	Serious impact on safety, e.g., fatality and/or Serious impact on engine performance e.g., engine stop



			Frequency				
			1	2	3	4	5
			Low	Medium Low	Medium	Medium High	High
Severity	3	High	4	5	6	7	8
	2	Medium	3	4	5	6	7
	1	Low	2	3	4	5	6

Broadly acceptable area	Tolerable area	Intolerable area

Fig. 3. Risk matrix for FMEA.

3.2. Fuzzy logic

A crisp set is a collection of countable elements, whereas a fuzzy set expresses elements through a membership function. According to the fuzzy logic of the fuzzy set theory, the fuzzy set $\tilde{a}$ in the entire set X is expressed as $\mu_{\tilde{a}}(x)$ in which each element x of X is related to some real number in the interval $[0, 1]$. The function value $\mu_{\tilde{a}}(x)$ denotes the degree of membership for x within $\tilde{a}$. Furthermore, when the fuzzy set $\tilde{a}$ in the entire set X is $\exists x_i \in X,\ \mu_{\tilde{a}}(x) = 1$, it is called a normalized fuzzy set. Fuzzy shape modeling is required to predict the positive index calculated according to the degree of membership, and such modeling is generally performed assuming triangular, standard distribution, trapezoidal, exponential, and L–R fuzzy shapes. In this study, the fuzzy shape is modeled assuming a triangular shape, with the triangular fuzzy number $\tilde{a}$ defined as (a_1, a_2, a_3). The membership function $\mu_{\tilde{a}}(x)$ of the triangular fuzzy number $\tilde{a}$ is expressed as Equation 1 (Zimmermann, 2011).

$$\mu\_\tilde{a}\ (x) = \begin{cases} 0 & x < a_1 \\ \frac{(x - a_1)}{(a_2 - a_1)}, & a_1 \leq x \leq a_2 \\ \frac{(x - a_3)}{(a_3 - a_2)}, & a_2 \leq x \leq a_3 \\ 0 & x > a_3 \end{cases} \qquad (1)$$

The result of the addition and subtraction of any two triangular fuzzy numbers is also a triangular fuzzy number, but the result of multiplication is an approximate triangular fuzzy number. Given two triangular fuzzy numbers $\tilde{a} = (a_1, a_2, a_3)$ and $\tilde{b} = (b_1, b_2, b_3)$, the arithmetic calculation of two fuzzy numbers is as follows (Chen, 2000; Zimmermann, 2011):

$$\tilde{a}\,(+)\,\tilde{b} = [a_1 + b_1, a_2 + b_2, a_3 + b_3]\ , \qquad (2)$$

$$\tilde{a}\,(-)\,\tilde{b} \;=\; [a_1 - b_1, a_2 - b_2, a_3 - b_3] \quad , \qquad (3)$$

$$\tilde{a}\,(\times)\,\tilde{b} \;=\; [a_1 \times b_1, a_2 \times b_2, a_3 \times b_3] \quad , \qquad (4)$$

$$\tilde{a}\,(/)\,\tilde{b} \;=\; [a_1 / b_3, a_2 / b_2, a_3 / b_1]\,. \qquad (5)$$

3.3. Hazard ranking via fuzzy TOPSIS-based FMEA

3.3.1. Overview of fuzzy TOPSIS FMEA

A multi-criteria decision-making problem with *m* alternatives, *n* decision criteria, and *K* decision makers is as follows.

$$D = \begin{array}{c|cccc} & C_1 & C_2 & \cdots & C_n \\ A_1 & \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \tilde{x}_{1n} \\ A_2 & \tilde{x}_{21} & \tilde{x}_{22} & \cdots & \tilde{x}_{2n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ A_m & \tilde{x}_{m1} & \tilde{x}_{m2} & \cdots & \tilde{x}_{mn} \end{array} \qquad (6)$$

$$W = \left[w_1, w_{2,} \;\cdots\; w_n\right] , \qquad (7)$$

where i = 1, …, m , j = 1, …, n, $A_1, A_2, \ldots, A_m$ are the alternatives to choose from (hazards in this study), $C_1, C_2, \ldots, C_n$ are the criteria for decision making (risk factors in this study), and w_j is the weight for each criterion of the decision maker.

The steps to apply the TOPSIS method to the fuzzy data of the fuzzy multi-criteria decision-making problem are as follows: In Step 1, the weights for risk factors are derived. In a fuzzy multi-criteria decision-making problem, the weight $\tilde{w}_j$ for the risk factor C_j can be measured as a positive triangular fuzzy number (Chen, 2000). In Step 2, a fuzzy decision matrix that is the result of an expert evaluation of hazards is derived.

$$\tilde{x}_{ij} \;=\; \frac{1}{K}\left[\tilde{x}_{ij}^{1}(+)\tilde{x}_{ij}^{2}(+)\cdots(+)\tilde{x}_{ij}^{K}\right] \qquad (8)$$

In Step 3, the measured values evaluated by different scales in the multi-criteria decision-making problem are normalized. The normalized fuzzy decision matrix is as follows:

$$\tilde{R} \;=\; \left[\tilde{r}_{ij}\right]_{m\times n}, i = 1, 2, \ldots, m, j = 1, 2, \ldots, n, \qquad (9)$$

where B and C are sets of profit and cost criteria, respectively.

$$\tilde{r} \;=\; \left(\frac{\tilde{a}_{ij}}{c_j^*}, \frac{\tilde{b}_{ij}}{c_j^*}, \frac{\tilde{c}_{ij}}{c_j^*}\right), j \in B, \qquad (10)$$

$$\tilde{r} \;=\; \left(\frac{\tilde{a}_{ij}}{c_j^-}, \frac{\tilde{b}_{ij}}{c_j^-}, \frac{\tilde{c}_{ij}}{c_j^-}\right), j \in C, \qquad (11)$$

if $j \in B$, $C_j^* = C_{ij}$, and if $j \in C$, $C_j^- = C_{ij}$.

In Step 4, a normalized fuzzy decision matrix ($\tilde{V}$)) with different weights assigned to each risk factor is calculated from the normalized fuzzy decision matrix calculated in Step 3 (Equation 12) (Chen, 2000).

$$\tilde{V} = \left[\tilde{v}_{ij}\ \right]_{m \times n} \qquad (12)$$

In Step 5, the elements of the normalized positive triangular fuzzy number $\tilde{v}_{ij}, \forall\, i, j$ can be calculated according to the weighted normalized fuzzy decision matrix $\tilde{V}$. The fuzzy positive ideal solution (FPIS A^*) and the fuzzy negative ideal solution (FNIS A^-) are calculated as follows (Chen, 2000), where, $\tilde{v}_j^* = (1,1,1), \tilde{v}_j^- = (0,0,0)$, and $j = 1, 2, \ldots, n$.

$$A^* = \{\tilde{v}_1^*, \tilde{v}_2^*, \ldots, \tilde{v}_n^*\},\ A^- = \{\tilde{v}_1^-, \tilde{v}_2^-, \ldots, \tilde{v}_n^-\} \qquad (13)$$

In Step 6, the distances from FPIS A^* and FNIS A^- for each alternative are calculated using the n-dimensional Euclidean distance as follows (Chen, 2000):

$$d_i^* = \sum_{j=1}^{n} d_v\left(\tilde{v}_{ij}, \tilde{v}_j^*\right), \qquad d_i^- = \sum_{j=1}^{n} d_v\left(\tilde{v}_{ij}, \tilde{v}_j^-\right) \qquad (14)$$

In the final step, the relative closeness coefficient CC of each alternative (hazard) is calculated to finally determine the risk rank of all the hazards (Chen, 2000).

$$CC_i = \frac{d_i^*}{d_i^* + d_i^-}, i = 1, 2, \ldots, m. \qquad (15)$$

As the value of CC_i converges to 1, the alternative approaches FPIS A^+ and recedes from FNIS A^-, where the alternative with the highest closeness coefficient represents the optimal alternative (Salih et al., 2019).

3.3.2. Application of fuzzy TOPSIS FMEA to LPG marine engine system

Because the LPG fuel marine engine system, the subject of this study, is the first engine developed for marine use in South Korea, the risk assessment according to the conventional FMEA method lacks objectivity owing to the lack of existing data and experience. Therefore, the following fuzzy TOPSIS method was applied to objectively evaluate and derive the risk ranking for risk factors and multiple hazards (failure modes).

The expert group for the case study comprised experts from academia, government, and a classification society who majored in marine engineering and had on-board experience, including manufacturers of LPG-fueled marine engines. Four experts evaluated the 89 alternatives (hazards) identified through FMEA. For risk factors, it is intended to apply five evaluation criteria from the three evaluation perspectives with the addition of detectability from the two (frequency and severity) factors considered in FMEA. Table 4 shows the linguistic variables for detectability and the corresponding fuzzy number used in this study.

Table 4 Linguistic variables and the corresponding fuzzy numbers for detectability in fuzzy TOPSIS (Wang et al., 2009).

Linguistic variable	Symbol	Definition	Fuzzy number
High	H	High chance the design control will detect a potential cause of failure or subsequent failure mode	(0, 0, 0.3)
Medium High	MH	Medium high chance the design control will detect a potential cause of failure or subsequent failure mode	(0, 0.25, 0.5)
Medium	M	Medium chance the design control will detect a potential cause of failure or subsequent failure mode	(0.3, 0.5, 0.7)
Medium Low	ML	Medium low chance the design control will detect a potential cause of failure or subsequent failure mode	(0.5, 0.75, 1)
Low	L	Low chance the design control will detect a potential cause of failure or subsequent failure mode	(0.7, 1, 1)

Detectability is an evaluation measure of whether users can detect an accident before it occurs; it measures the likelihood that a failure may be predicted, thereby preventing or mitigating the accident in advance (Cheraghi et al., 2019). Table 5 shows the linguistic scales for the three risk factors used in this study, including frequency, severity, and detectability, as well as their fuzzy numbers (Chen and Hwang, 1992; Lazakis and Ölçer, 2016).

Table 5 Linguistic variables and the corresponding fuzzy numbers in fuzzy TOPSIS.

Linguistic variable	Symbol	Triangular fuzzy number
Low	L	(0, 0, 0.3)
Medium low	ML	(0, 0.25, 0.5)
Medium	M	(0.3, 0.5, 0.7)
Medium high	MH	(0.5, 0.75, 1)
High	H	(0.7, 1, 1)

Table 6 shows the results of risk factor assessment with a linguistic scale for each expert using Table 6 to derive the weights for risk factors in Step 1, as well as the resulting fuzzy number.

Table 6 Summary of linguistic ratings evaluated by experts and the related fuzzy numbers.

Risk factors	Experts 1	Experts 2	Experts 3	Experts 4

	(Maritime Professor)	(Engine Manufacturer)	(Class surveyor)	(Government Officer)
Frequency	MH (0.5, 0.75, 1)	M (0.3, 0.5, 0.7)	MH (0.5, 0.75, 1)	MH (0.5, 0.75, 1)
Severity	M (0.3, 0.5, 0.7)	M (0.3, 0.5, 0.7)	MH (0.5, 0.75, 1)	H (0.7, 1, 1)
Detectability	ML (0, 0.25, 0.5)	ML (0, 0.25, 0.5)	M (0.3, 0.5, 0.7)	M (0.3, 0.5, 0.7)

In this study, the normalized fuzzy decision matrix (Step 3) for risk factors such as frequency, severity, and detectability was calculated using Equation (10) as the gain criterion. In Step 7, the relative closeness coefficients for each risk factor were obtained, and the risks were finally rated in the order of the risk factors with the highest closeness coefficient.

3.4. FSA methodology

3.4.1. Overview of FSA methodology

The FSA is a risk assessment technique approved by the IMO to assess the risks associated with the shipping industry as well as to determine the costs and benefits of a RCO for reducing potential risks (IMO, 2018b). The FSA consists of six steps, beginning with the preparation for safety assessment, including the definition of the target ship or system, followed by hazard identification, risk analysis, preparation of RCOs, cost-benefit analysis, and decision-making recommendation. , as shown in Fig. 4.

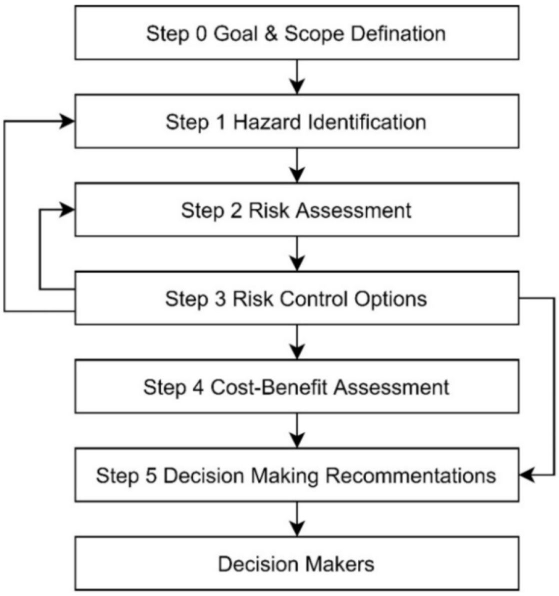


Fig. 4. General approach of a formal safety assessment (FSA) (Wang et al., 2020).

The risk assessment in Step 2 involves a process of quantifying individual accident types and related risks. An ETA model is developed for each accident category defined in Step 1, and the quantitative risk for each accident type is analyzed using this model, where risk is broadly classified into three categories: life risk, environmental risk, and property risk, and life risk is further classified into individual risk and group risk. Group risk refers to the collective risk of all individuals exposed to risk when all personnel directly or indirectly related to the target ship (including crew, all workers, and all passengers) are exposed to risk. It is mainly expressed as the risk of death, that is, the number of deaths, and among them, the potential loss of life (PLL) is the expected number of fatalities per year (fatality per ship-year) that can efficiently express the group risk quantitatively (KR, 2015).

Step 3 aims to identify the measures for controlling risks, and the measures for reducing the estimated risk to the lowest possible level within a reasonable range are established and implemented. Among the results from Step 2, the areas with the greatest risk are identified, the risk control measures (RCMs) for each risk factor are identified, and the RCO is developed by combining these RCMs.

Step 4 aims to identify and compare the costs and benefits associated with the implementation of each RCO identified in Step 3. The cost and effectiveness of the application of the RCO are generally evaluated based on the gross cost of averting a fatality (GCAF) and the net cost of averting a fatality (NCAF), which are expressed as follows:

$$GCAF = \frac{\Delta C}{\Delta R}, \qquad (16)$$

$$NCAF = \frac{\Delta C - \Delta B}{\Delta R}, \qquad (17)$$

where Δ C is the cost incurred over the lifespan of the ship when applying RCO, Δ B is the economic benefit over the lifespan of the ship as a result of applying RCO, and Δ R is the amount of risk reduction in terms of the reduction of casualties owing to the application of RCO.

In addition, the net present value (NPV) is mainly used to derive the cost ($\Delta\ C$) during the life of the ship owing to the application of RCO used to calculate GCAF and NCAF (IMO, 2007b).

$$NPV = A + \frac{X_1}{(1+r)} + \frac{X_2}{(1+r)^2} + \cdots + \frac{X_T}{(1+r)^T} = A + \sum_{t=1}^{T} \frac{X_t}{(1+r)^t} \qquad (18)$$

where X_T is the cost or benefit required at time t (the flow period for the cost required) according to the application of the RCO, A is the initial cost required for RCO application, r is the depreciation rate, and T is the lifespan of the ship. Although not specified in the cost-benefit analysis, the suggested values for NCAF and

GCAF considering social indicators are shown in Table 7 (IMO, 2018b). In other words, additional review is required for RCOs with NCAF and GCAF values exceeding US $3 million as a result of the analysis.

Table 7 Cost-effectiveness criteria (IMO, 2018b).

List of Criteria	GCAF (US $)	NCAF (US $)
Criterion covering risk of fatality, injuries and ill health	3 million	3 million
Criterion covering only risk of fatality	1.5 million	1.5 million
Criterion covering only risk of injuries and ill health	1.5 million	1.5 million

In Step 5, a cost-effective decision is made using the information in Step 1–4, and it is proposed for enable determining the acceptability of the risk in making a decision on the IMO conventions.

3.4.2. Application of FSA methodology to LPG marine engine system

In this study, in Step 0–1, risk factors were identified and risk ranks were subdivided through FMEA and fuzzy TOPSIS FMEA (the techniques described in Section 3.1–3.3). Accordingly, the RCO is identified for risk factors with a high risk rank (Step 3), the cost-effectiveness of the selected RCOs is assessed (Step 4), and specific measures for the safe operation of a coastal ship equipped with an LPG marine engine system are proposed (Step 5). As an alternative fuel for ships, LPG fuel has many advantages, particularly when applied to fishing vessels in consideration of LPG characteristics and market competitiveness (Yeo et al., 2022). Therefore, with the aim of proposing safety standards for fishing vessels with a high possibility of conversion to using LPG, domestic fishing vessel accident data for 30 years from 1985 to 2015 were analyzed as basic data for developing an ETA model in the second stage, and the distribution of accident types is presented in Table 8.

Table 8 Breakdown of historic accident data on accident categories during 1985–2020[a] (Fisheries statistics, 2021; Statistics of marine accidents, 2021).

Accident category	Number of accidents	Accidents frequency (per ship-year)
Collision	7066	2.5×10^{-3}
Grounding	1971	7.0×10^{-4}
Contact	160	5.7×10^{-5}
Fire/Explosion	1920	6.8×10^{-4}
Machinery damage [b]	9323	3.3×10^{-3}

Capsizing	788	2.8×10^{-4}
Safety accident(Death/Injuries)	1330	4.7×10^{-4}
Sinking	1403	5.0×10^{-4}
Others [c]	7328	2.6×10^{-3}
Total	31289	1.1×10^{-2}

[a] A total of 2,829,820 fishing vessels were registered during the same period.

[b] Engine accidents include damage to main engines, boilers, and auxiliary engines, as well as pumps for supplying fuel, lubricating oil, air, and coolant to the main engines, boilers, and auxiliary engines, related to ship propulsion.

[c] Propulsion shaft damage, steering gear damage, accessory damage, and marine pollution.

Fig. 5 and 6 show the ETA model and results corresponding to Step 2, based on the above accident statistics (Table 9). When the LPG marine engine system in Section 2 is mounted on a fishing vessel, the possible accidents due to engine failure include drift grounding owing to the inability of using the main engine during voyage and fire/explosion due to lack of suitable maintenance (IMO, 2007c). Therefore, this study intends to analyze the ETA model for fire/explosion and drift grounding and determine the total potential loss of life for various scenarios according to the accident type, where the risk model for each accident type, each scenario, and the quantification of the related probabilities utilizes the existing research data on the operation of LNG fuel carriers with safety standards currently provided in the International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IMO, 2007c). In Step 3, while various methods are considered to reduce the risk, it is necessary to consider the operation type of the ship provided with this engine system and the human factors of the crew. Accordingly, preventive maintenance activity that can be conveniently and efficiently implemented on ships and that has often been adopted to reduce the number of failures of equipment was selected as an RCO (Jimenez et al., 2020). For the cost-benefit analysis in Step 4, the number of people on board is set to 30, with the average lifespan of the ship being 40 years and the depreciation rate being 5%; here, the accident location and property damage are assumed to be the engine room and engine damage (total loss), respectively (IMO, 2007c).

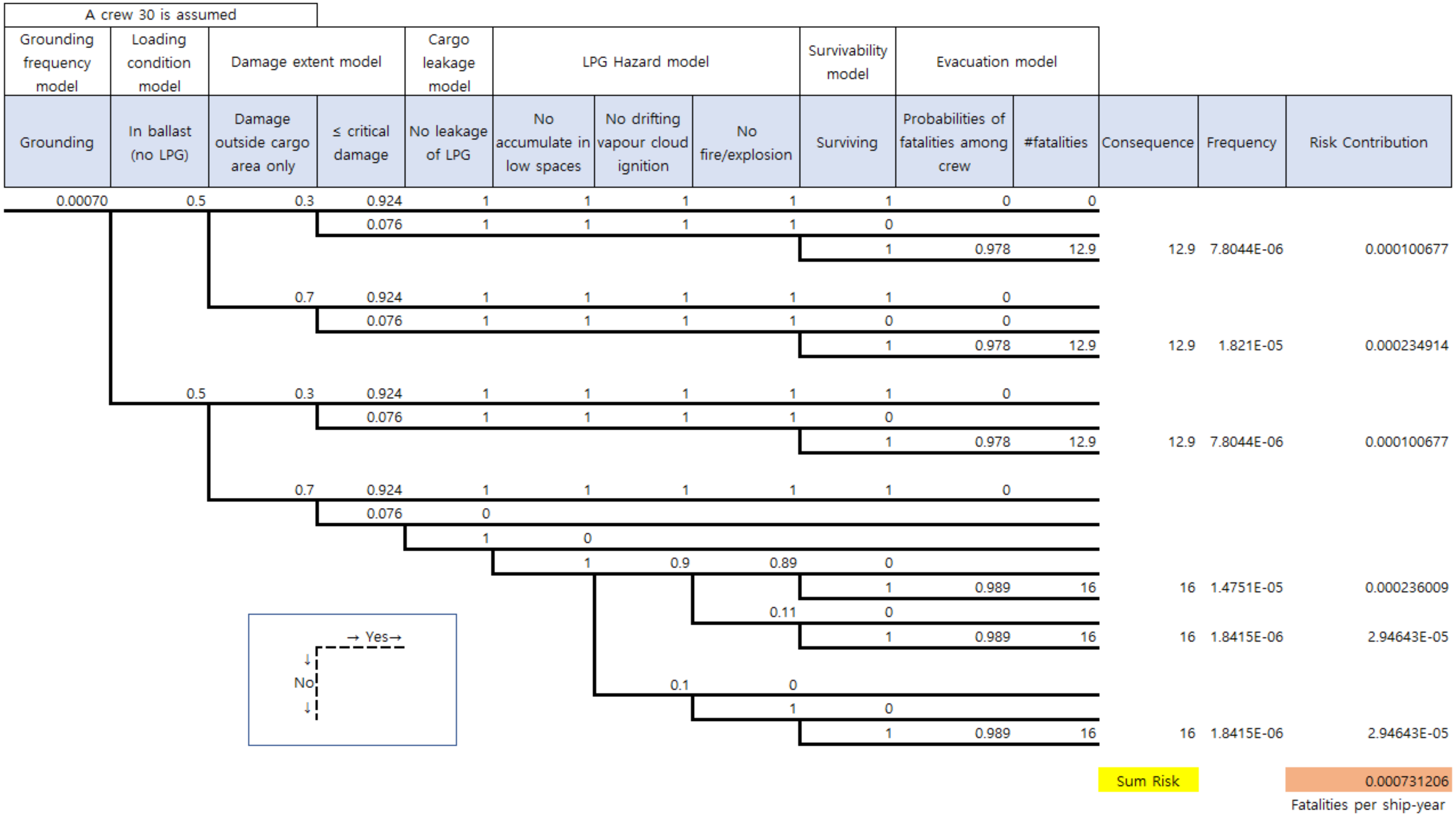


Fig. 5. Event tree for grounding scenario.

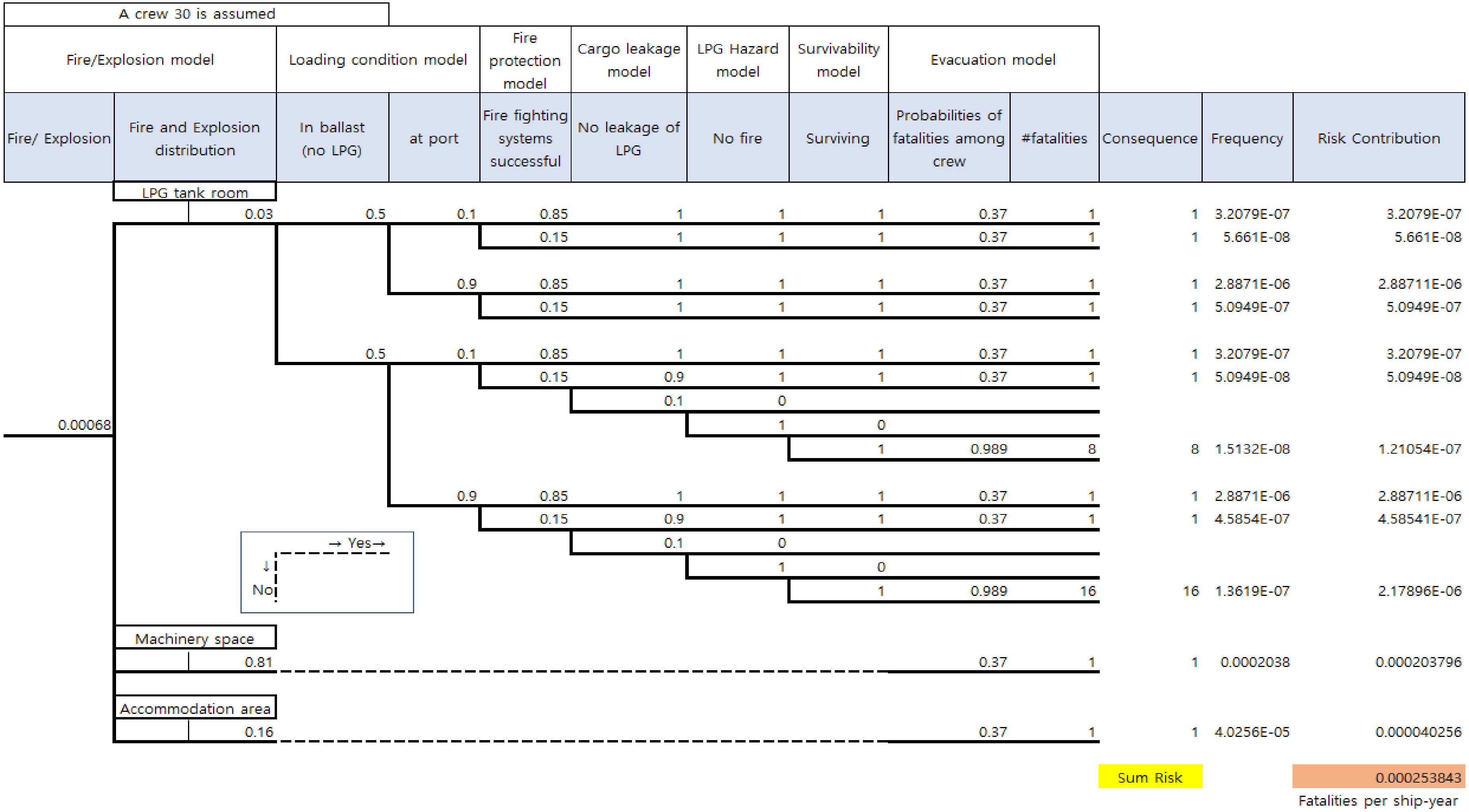
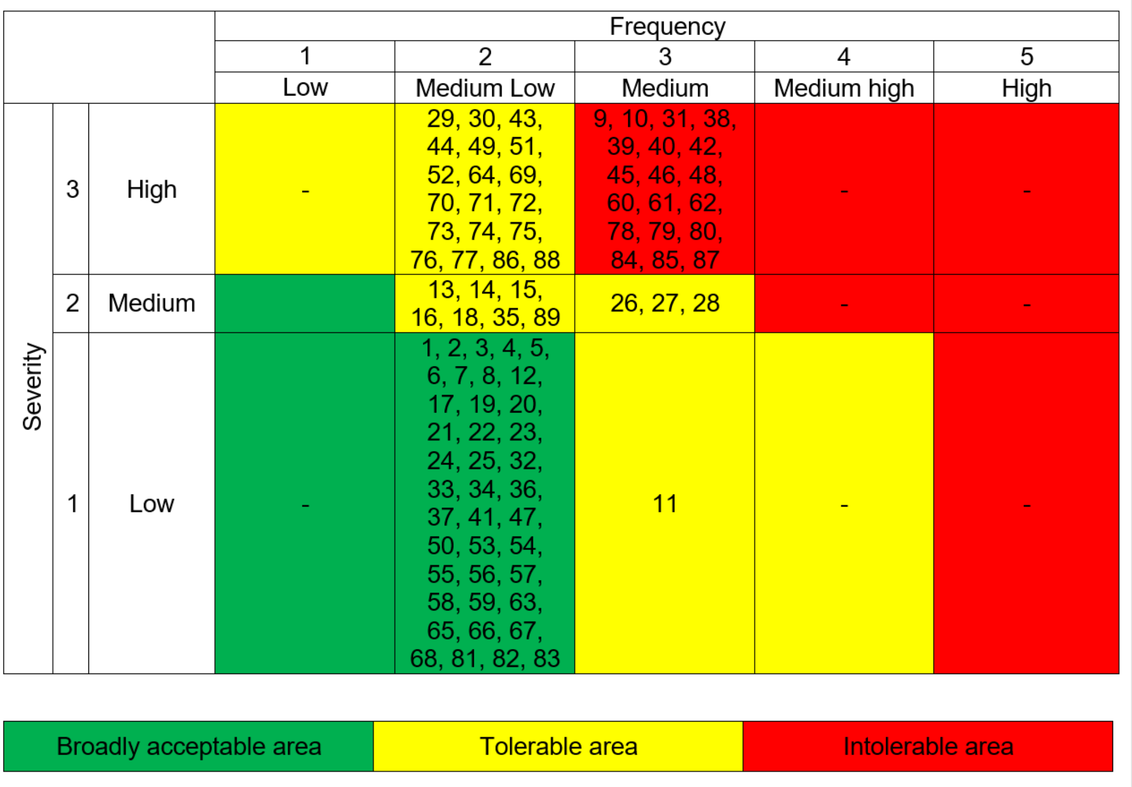


Fig. 6. Event tree for fire and explosion scenario.

4. Results

4.1. FMEA analysis

Owing to the lack of experience with LPG fuel marine engines, the failure mode for each element was identified through continuous meetings and discussions (not a single workshop), and the impact according to the safety tolerance standards was evaluated. As shown in Fig. 7. & Table 9, the failure mode of each individual element was investigated and evaluated to safely manage the entire system by dividing the entire system into individual components according to the FMEA technique in this study. The cause of the failure, the process of occurrence, and the possibility of occurrence were identified by analyzing the degree of influence of the failure of individual devices constituting the system. As a result of FMEA, a total of 89 hazards were identified and assessed. Of these, 19 were identified to fall within the intolerable area, 30 within the tolerable area (ALARP, as low as reasonably practicable), and 40 within the broadly acceptable area. Most failure modes were assessed to be ALARP or acceptable. According to the result of the evaluated risk index, the risk ranks were divided into four groups (the values range from 3 to 6).



			Frequency				
			1	2	3	4	5
			Low	Medium Low	Medium	Medium high	High
Severity	3	High	-	29, 30, 43, 44, 49, 51, 52, 64, 69, 70, 71, 72, 73, 74, 75, 76, 77, 86, 88	9, 10, 31, 38, 39, 40, 42, 45, 46, 48, 60, 61, 62, 78, 79, 80, 84, 85, 87	-	-
	2	Medium		13, 14, 15, 16, 18, 35, 89	26, 27, 28	-	-
	1	Low	-	1, 2, 3, 4, 5, 6, 7, 8, 12, 17, 19, 20, 21, 22, 23, 24, 25, 32, 33, 34, 36, 37, 41, 47, 50, 53, 54, 55, 56, 57, 58, 59, 63, 65, 66, 67, 68, 81, 82, 83	11	-	-

Broadly acceptable area	Tolerable area	Intolerable area

FIG. 7. FMEA analysis results with risk matrix.

Table 9 Results of FMEA analysis (Summary).

Hazard No.	List of Components	Failure; Cause	Consequence(s)	End Effect	Frequency Index	Severity Index	Risk Index[a]
1	Fuel Pressure Sensor	Short circuit, signal failure or failure in the computer input	Signal out of range.	Continuous operation on LPG.	2	1	3
2	Fuel Pressure Sensor	The sensor gives a valid though lower signal than actual pressure.	Wrong value used in computations.	Continuous operation on LPG.	2	1	3
3	Fuel Pressure Sensor	The sensor gives a valid though higher signal than actual pressure.	Wrong value used in computations.	Continuous operation on LPG.	2	1	3
4	LPG supply main v/v	Wire breakage, short circuit, sensor failure	Inconsistent feedback in some states	Continuous operation on LPG.	2	1	3
5	LPG purge main v/v	Wire breakage, short circuit, sensor failure	Inconsistent feedback in some states	Continuous operation on LPG.	2	1	3
6	Purge, Fuel outlet solenoid valve	Wire breakage, signal failure or failure in the computer input.	Valve (F4) control failure	Engine may not be purged sufficiently.	2	1	3
7	Purge, Fuel outlet solenoid valve	Short circuit, signal failure or failure in the computer input	Valve (F4) control failure	LPG is leak to the atmosphere.	2	1	3
8	Main Valve Opened Switch	Wire breakage, short circuit (constant signal), sensor failure	Inconsistent feedback in some states	Continuous operation on LPG.	2	1	3
9	Phase Sensor	Wire breakage, short circuit (constant signal), sensor failure	Signal out of range	Engine may be stopped.	3	3	6
10	Electric Throttle Actuator sensing	Wire breakage, short circuit (constant signal), sensor failure	Inconsistent feedback in some states	Engine may be shutdown.	3	3	6
11	Ignition Coil & Spark Plug	Wire breakage, short circuit (constant signal), sensor failure	Combustion is out of control	Continuous operation on LPG.	3	1	4
12	Three Way Catalyst	Wire breakage, short circuit (constant signal), sensor failure	Inconsistent feedback in some states.	Continuous operation on LPG.	2	1	3
13	Air pressure sensor	Wire breakage, short circuit, sensor failure	Signal out of range.	It may cause incomplete combustion.	2	2	4
14	Air pressure sensor	The sensor gives a valid though lower signal than actual pressure.	Wrong value used in computations.	It may cause incomplete combustion.	2	2	4
15	Air pressure sensor	The sensor gives a valid though higher signal than actual pressure.	Wrong value used in computations.	It may cause incomplete combustion.	2	2	4
16	Air Temp. sensor	Wire breakage, short circuit, sensor failure	Signal out of range.	It may be occurred knocking in cylinder.	2	2	4
17	Air Temp. sensor	The sensor gives a valid though lower signal than actual pressure.	Wrong value used in computations.	Continuous operation on LPG.	2	1	3
18	Air Temp. sensor	The sensor gives a valid though higher signal than actual pressure.	Wrong value used in computations.	It may be occurred knocking in cylinder.	2	2	4
19	Fuel Pressure Sensor	Short circuit, signal failure or failure in the computer input	Signal out of range.	Continuous operation on LPG.	2	1	3
20	Fuel Pressure Sensor	The sensor gives a valid though lower signal than actual pressure.	Wrong value used in computations.	Continuous operation on LPG.	2	1	3
21	Fuel Pressure Sensor	The sensor gives a valid though higher signal than actual pressure.	Wrong value used in computations.	Continuous operation on LPG.	2	1	3
22	LPG supply temperature sensor	Wire breakage, short circuit, sensor failure	Signal out of range.	Continuous operation on LPG.	2	1	3
23	LPG supply temperature sensor	The sensor gives a valid though lower signal than actual value.	Wrong value used in computations.	Continuous operation on LPG.	2	1	3
24	LPG supply temperature sensor	The sensor gives a valid though higher signal than actual value.	Wrong value used in computations.	Continuous operation on LPG.	2	1	3
25	EGR Valve	Wire breakage, short circuit (constant signal), sensor failure	Inconsistent feedback in some states.	NOx may be increased in the exhaust gas.	2	1	3
26	Lambda sensor	Wire breakage, short circuit, sensor failure, power failure	Signal out of range.	Continuous operation on LPG with de-rating.	3	2	5
27	Lambda sensor	The sensor gives a valid though lower signal than actual value.	Wrong value used in computations.	Continuous operation on LPG with de-rating.	3	2	5
28	Lambda sensor	The sensor gives a valid though higher signal than actual value.	Wrong value used in computations.	Continuous operation on LPG with de-rating.	3	2	5
29	Exh. Gas Temp. sensor	Wire breakage, short circuit, sensor failure	Signal out of range.	Engine will be shutdown	2	3	5
30	Exh. Gas Temp. sensor	The sensor gives a valid though lower signal than actual pressure.	Wrong value used in computations.	Engine will be shutdown	2	3	5
31	Exh. Gas Temp. sensor	The sensor gives a valid though higher signal than actual pressure.	Wrong value used in computations.	Engine will be shutdown	3	3	6
32	Jacket Water Temp. sensor	Wire breakage, short circuit, sensor failure	Signal out of range.	Continuous operation on LPG.	2	1	3
33	Jacket Water Temp. sensor	The sensor gives a valid though lower signal than actual pressure.	Wrong value used in computations.	Continuous operation on LPG.	2	1	3
34	Jacket Water Temp. sensor	The sensor gives a valid though higher signal than actual pressure;	Wrong value used in computations.	Continuous operation on LPG.	2	1	3
35	Knock Sensor	Wire breakage, short circuit (constant signal), sensor failure	Inconsistent feedback in some states	Continuous operation on LPG with de-rating.	2	2	4
36	Knock Sensor	The sensor gives a valid though lower signal than actual value.	Wrong value used in computations.	Continuous operation on LPG.	2	1	3

37	Knock Sensor	The sensor gives a valid though higher signal than actual value.	Wrong value used in computations.	Continuous operation on LPG.	2	1	3
38	Engine Speed Sensor	Wire breakage, short circuit (constant signal), sensor failure	Inconsistent feedback in some states	Engine will be shutdown	3	3	6
39	Engine Speed Sensor	The sensor gives a valid though lower signal than actual value.	Wrong value used in computations	Engine will be shutdown	3	3	6
40	Engine Speed Sensor	The sensor gives a valid though higher signal than actual value.	Wrong value used in computations.	Engine will be shutdown	3	3	6
41	Electronic control Unit	Wire breakage, short circuit, sensor failure	Signal out of range.	Continuous operation on LPG.	2	1	3
42	Electronic control Unit	Electric shortage. Hardware wearing out.	Valve control is not made properly.	Engine will not be operable.	3	3	6
43	Power supply to ECU	Wire breakage, signal failure or failure in the computer input	Constant 'Power failure' signal.	Engine may be not running properly.	2	3	5
44	Power supply to ECU	Short circuit, signal failure or failure in the computer input	Valve controls are not made properly.	Engine may be not running properly.	2	3	5
45	Each sensors	Non-controlled state (the electronic control units are turned off)	Impossible to ready and operate	Engine may be stopped.	3	3	6
46	Each sensors	Non-controlled state (the electronic control units are out of control)	Impossible to ready and operate	Engine may be stopped.	3	3	6
47	Filter , PDT	Wire breakage, short circuit, sensor failure	Signal out of range.	Continuous operation on LPG.	2	1	3
48	Filter, PDT	The sensor gives a valid though lower signal than actual pressure.	Wrong value used in computations.	Engine may be stopped	3	3	6
49	Filter, PDT	The sensor gives a valid though higher signal than actual pressure.	Wrong value used in computations.	Continuous operation on LPG.	2	3	5
50	Purge line pressure sensor	Wire breakage, short circuit, sensor failure, signal out of range.	Signal out of range.	Continuous operation on LPG.	2	1	3
51	Purge line pressure sensor	The sensor gives a valid though lower signal than actual value.	Wrong value used in computations.	Engine will be shutdown	2	3	5
52	Purge line pressure sensor	The sensor gives a valid though higher signal than actual value.	Wrong value used in computations.	Engine will be shutdown	2	3	5
53	LPG flow sensor	Wire breakage, short circuit, sensor failure	Signal out of range.	Continuous operation on LPG.	2	1	3
54	LPG flow sensor	The sensor gives a valid though lower signal than actual value.	Wrong value used in computations	Continuous operation on LPG.	2	1	3
55	LPG flow sensor	The sensor gives a valid though higher signal than actual value.	Wrong value used in computations.	Continuous operation on LPG.	2	1	3
56	Blow-off temperature sensor	Wire breakage, short circuit, sensor failure	No supervision of leaks.	Continuous operation on LPG.	2	1	3
57	Blow-off temperature sensor	The sensor gives a valid though lower signal than actual value.	False alarm for LPG leakage.	Continuous operation on LPG.	2	1	3
58	Blow-off temperature sensor	The sensor gives a valid though higher signal than actual value.	Risk of undetected LPG leakage.	LPG is leak to the atmosphere.	2	1	3
59	LPG supply system run signal	Supply pump is running when it should not run; Wire short-circuit	It may be started by mistake.	None.	2	1	3
60	LPG supply system press.signal	Wire breakage, short circuit, sensor failure	System not receive pressure set point.	Engine may be stopped.	3	3	6
61	LPG supply system press.signal	The signal has a legal though lower value than correct	The LPG delivers lower LPG pressure	Engine may be stopped.	3	3	6
62	LPG supply system press.signal	The signal has a legal though higher value than correct	The LPG delivers higher LPG pressure	Engine may be stopped.	3	3	6
63	LPG shutdown signal	Not activated when it should be activated; Wire breakage	System not be shutdown automatically.	None.	2	1	3
64	LPG shutdown signal	Activated when it should not be activated; Wire short-circuit	System may be shutdown accidently.	Engine may be stopped.	2	3	5
65	Main power supply systems for engine conrol system	One main power supply unit failure	None	Continuous operation on LPG.	2	1	3
66	Main power supply systems for engine conrol system	Over- or under voltage of main supply	None	Continuous operation on LPG.	2	1	3
67	Individual power supply failure for ECS	One unit power supply failure	None	Continuous operation on LPG.	2	1	3
68	Individual power supply failure for ECS	Over- or under voltage of one unit power supply	Specific controller gets too high voltage.	Continuous operation on LPG.	2	1	3
69	Disconnected with safety system andg cotrol system	Non-controlled state (the ECUs are turned off or out of control)	Power supply to safety system and control system stopped.	Engine will be shut-down.	2	3	5
70	Disconnected with PMS, AMS and control system	Non-controlled state (the ECUs are turned off or out of control)	Safety system is not work.	Engine will be shut-down.	2	3	5
71	Disconnected with safety system, and no getting signal from gen Volt/amp and gas detection sensor	Non-controlled state (the ECUs are turned off or out of control)	Alarm is not released.	Engine will be shut-down.	2	3	5
72	Generator Volt/Amp	Wire breakage, short circuit (constant signal), sensor failure	Alarm is released.	Engine may be stopped.	2	3	5
73	Gas detection sensor	Wire breakage, short circuit (constant signal), sensor failure	Alarm is released.	Engine may be stopped.	2	3	5

74	Disconnected with PMS, safety system and ECS	Non-controlled state (the ECUs are turned off or out of control)	Generator condition cannot be transferred to PMS.	Engine will be shut-down.	2	3	5
75	Disconnected with control system, and no getting signal from sensors, etc	Non-controlled state (the ECUs are turned off or out of control)	Main engine does not work properly.	Engine will be shut-down.	2	3	5
76	Safety system	No signal: Wire breakage, failure in ME-ECS controller input	LPG Shutdown is released.	Engine will be shut-down.	2	3	5
77	Safety system	Constant signal; Short circuit, failure in ME-ECS controller input	LPG Shutdown cannot be signalled.	Engine Shutdown is not made properly.	2	3	5
78	Crankshaft position sensor	Wrong signal pattern; Wire breakage, short circuit, sensor failure	Crankshaft position is lost.	Engine will be shut-down.	3	3	6
79	LPG Supply system Run from ECR	Not activated when it should be activated; Wire breakage	The LPG supply system may stop.	Engine may be stopped.	3	3	6
80	N2 Supply valve position	Wire breakage, short circuit (constant signal), sensor failure	Inconsistent feedback in some states.	Engine may be stopped.	3	3	6
81	N2 supply line, pressure sensor	Wire breakage, short circuit, sensor failure	Signal out of range.	None.	2	1	3
82	N2 supply line, pressure sensor	The sensor gives a valid though lower signal than actual pressure.	Wrong value used in computations.	None.	2	1	3
83	N2 supply line, pressure sensor	The sensor gives a valid though higher signal than actual pressure.	Wrong value used in computations.	Engine may not be purged sufficiently.	2	1	3
84	LPG shutdown signals from activating sensor abnormal	Failure in transmitting system controller output.	LPG Shutdown cannot be activated.	Shutdown not be automatically activated.	3	3	6
85	LPG shutdown signals from activating sensor abnormal	Short circuit or failure in computer output.	LPG Shutdown by mistake.	Engine shut-down by mistake	3	3	6
86	Shut-down buttons in Local Operation	Open circuit loop; Cable failure.	LPG Shutdown cannot be activated.	Shutdown not be automatically activated.	2	3	5
87	Panel	Short circuit or failure in computer output.	Engine shut-down by mistake.	Engine shut-down by mistake	3	3	6
88	CAN	Cable failure, missing impedance resistor short-circuit	None	Engine will be shut-down.	2	3	5
89	LAN communication	Cable failure, missing impedance resistor short-circuit	None	Continuous operation on LPG with de-rating.	2	2	4

LPG: Liquefied petroleum gas, EGR: Exhaust gas recirculation, ECU: Electric control unit, PDT: Pressure differential transmitter, ECS: Engine control system, PMS: power managenment system.

[a] Broadly acceptable area (2–3), Tolerable area (4–5), Intolerable area (6–8).

4.2. Fuzzy TOPSIS FMEA analysis

According to Table 9, for the 89 hazards identified through FMEA, four experts applied the evaluation criteria as shown in Table 4 and 5 to three risk factors, including frequency, severity, and detectability. Table 10 shows the results of fuzzy TOPSIS FMEA. The higher the closeness coefficient CC_i, the greater the risk of the hazard. Risk ranks can be divided into 28 groups by classifying a total of 89 hazards according to the magnitude of the closeness coefficient. According to Table 10, the risk ranks of the 19 hazards in the group (risk index: 6) with the highest risk index value determined via FMEA are precisely assigned through the fuzzy TOPSIS FMEA. In addition, as a result of the fuzzy TOPSIS FMEA, the risk ranks of some hazards (hazard no. 69, 70, 74, 75, 77, and 86) that were included in the tolerable area according to the FMEA were analyzed to be higher than those of some hazards in the intolerable area (hazard no. 31 and 42) with a larger closeness coefficient. As a result of analyzing the hazards with high risk ranks and classifying them by components (excluding duplicates), the main critical hazards are LPG pressure sensors including signal line, LPG supply line filter, LPG filter differential pressure transmitter, phase sensor, electric throttle actuator sensor, and engine control unit, as shown in Fig. 8.

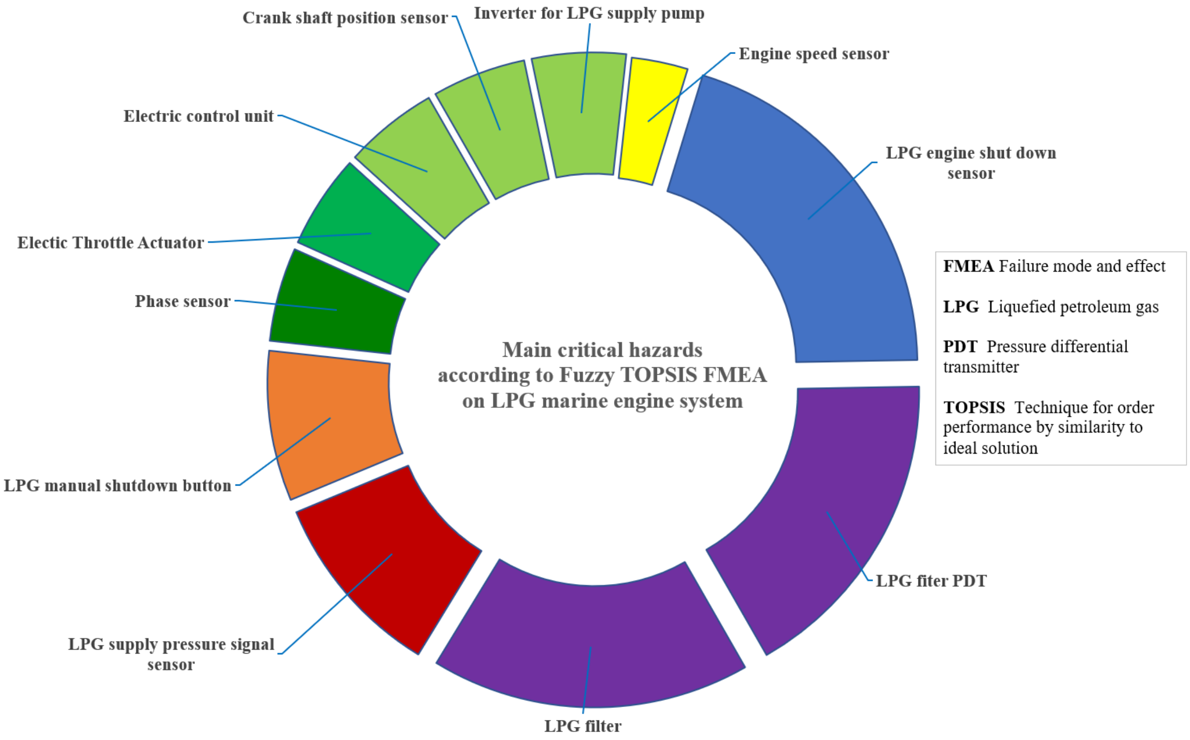


FIG. 8. Main critical hazards based on fuzzy TOPSIS FMEA for LPG marine engine system.

Table 10 Risk ranking by fuzzy TOPSIS FMEA.

Hazard no.	Distance		CC_i	Rank no.	Hazard no.	Distance		CC_i	Rank no.
	d_i^*	d_i^-				d_i^*	d_i^-		
1	1.958	0.718	0.268	79	46	1.302	1.457	0.528	7
2	1.958	0.718	0.268	79	47	1.943	0.738	0.275	61
3	1.958	0.718	0.268	79	48	1.203	1.601	0.571	2
4	1.958	0.718	0.268	79	49	1.491	1.248	0.456	28
5	1.958	0.718	0.268	79	50	1.943	0.738	0.275	61
6	1.958	0.718	0.268	79	51	1.506	1.228	0.449	36
7	1.716	0.963	0.359	52	52	1.506	1.228	0.449	36
8	1.709	1.003	0.370	47	53	1.943	0.738	0.275	61
9	1.302	1.457	0.528	7	54	1.943	0.738	0.275	61
10	1.302	1.457	0.528	7	55	1.943	0.738	0.275	61
11	1.565	1.178	0.429	42	56	1.834	0.911	0.332	55
12	1.943	0.738	0.275	61	57	1.834	0.911	0.332	55
13	1.695	0.995	0.370	44	58	1.608	1.136	0.414	43
14	1.710	0.975	0.363	48	59	1.834	0.911	0.332	55
15	1.710	0.975	0.363	48	60	1.215	1.572	0.564	3
16	1.710	0.975	0.363	48	61	1.234	1.550	0.557	4
17	1.958	0.718	0.268	79	62	1.234	1.550	0.557	4
18	1.710	0.975	0.363	48	63	1.943	0.738	0.275	61

19	1.943	0.738	0.275	61	64	1.491	1.248	0.456	28
20	1.943	0.738	0.275	61	65	1.958	0.718	0.268	79
21	1.943	0.738	0.275	61	66	1.958	0.718	0.268	79
22	1.943	0.738	0.275	61	67	1.958	0.718	0.268	79
23	1.943	0.738	0.275	61	68	1.943	0.738	0.275	61
24	1.958	0.718	0.268	79	69	1.354	1.421	0.512	23
25	1.867	0.804	0.301	58	70	1.340	1.444	0.519	18
26	1.521	1.184	0.438	39	71	1.491	1.248	0.456	28
27	1.521	1.184	0.438	39	72	1.491	1.248	0.456	28
28	1.521	1.184	0.438	39	73	1.491	1.248	0.456	28
29	1.407	1.329	0.486	27	74	1.361	1.430	0.512	21
30	1.392	1.350	0.492	26	75	1.361	1.430	0.512	21
31	1.346	1.403	0.510	24	76	1.491	1.248	0.456	28
32	1.943	0.738	0.275	61	77	1.340	1.444	0.519	18
33	1.943	0.738	0.275	61	78	1.302	1.457	0.528	7
34	1.716	0.963	0.359	52	79	1.302	1.457	0.528	7
35	1.695	0.995	0.370	44	80	1.302	1.457	0.528	7
36	1.867	0.804	0.301	58	81	1.943	0.738	0.275	61
37	1.867	0.804	0.301	58	82	1.801	0.949	0.345	54
38	1.317	1.437	0.522	14	83	1.943	0.738	0.275	61
39	1.317	1.437	0.522	14	84	1.160	1.668	0.590	1
40	1.317	1.437	0.522	14	85	1.302	1.457	0.528	7
41	1.943	0.738	0.275	61	86	1.360	1.453	0.517	20
42	1.346	1.403	0.510	24	87	1.246	1.558	0.556	6
43	1.491	1.248	0.456	28	88	1.491	1.248	0.456	28
44	1.506	1.228	0.449	36	89	1.695	0.995	0.370	44
45	1.317	1.437	0.522	14					

[a] Main critical hazards with high hazard ranks (1–14) according to fuzzy TOPSIS FMEA.

4.3. Developed RCOs for critical hazards

According to Table 10, the risk ranks were determined according to the magnitude of the closeness coefficient for a total of 89 hazards. Table 11 shows the results of applying the FSA technique described in Section 3.4.

Table 11 Cost-benefit assessment of the recommended RCO.

Items		
Risk Control Option Description		Risk-based maintenance (Periodically replace high risk ranked hazards[a])
Input to Cost estimate for RCO	Initial investment [b]	USD 2,000 (reference: Engine manufacturer)
	Annual cost [c]	USD 400
Fatalities per ship year initial (PLL)	Fire/explosion	2.03×10^{-4}

	Grounding (Drift)	2.19×10^{-4}
Number of fatalities lives saved[d] (ΔPLL)	Fire/explosion	3.06×10^{-5}
	Grounding (Drift)	4.38×10^{-5}
Probability of accident per ship	Fire/explosion	5.51×10^{-4}
	Grounding (Drift)	1.60×10^{-5}
Reduction probability of accident per ship[e]	Fire/explosion	8.26×10^{-5}
	Grounding (Drift)	3.19×10^{-6}
Cost associated (USD million)		0.10 (reference: Engine manufacturer)
Economic benefit (USD)	Fire/explosion	8.26
	Grounding (Drift)	0.32
Gross CAF (10^6 US/fatality)		2.98
Net CAF (10^6 US/fatality)		2.93

[a] main critical hazards (rank no. 1–14) according to Table 10.

[b] Initial cost of installation to address all critical hazards (rank no. 1–14) according to Table 10 at the time of new construction.

[c] Cost of replacement to address critical hazards (rank no. 1–14) according to Table 10 during the periodic inspection of the ship (every 5 years).

[d, e] It is assumed that the reduction rates of engine room fire/explosion accidents and drift grounding accidents due to engine system failure are 15% and 20%, respectively (IMO, 2007c).

While conducting the cost-benefit analysis, the upper limit was considered in terms of cost to obtain a conservative result, and accordingly, the NPV with the ship lifecycle (40 years) and a depreciation rate of 5% applied was 0.0089 USD—the cost (Δ C) of the ship for 40 years with RCO applied. The annual number of casualties due to fire/explosion and grounding (drift) reduces the risk by 3.06×10^{-5} *and* 4.38×10^{-5} per year, respectively, implying that it can reduce 0.00122 fatalities and 0.00175 fatalities per ship in 40 years, respectively (total Δ R = 0.00298). As mentioned in Section 3.4.2, the estimated cost (cost of engine replacement) due to property damage required for each accident scenario is US \$ 0.10 million, considering the purpose of this study. Substituting this into the accident reduction rate, the annual economic benefits of the ship obtained as a result of RCO application are US \$ 8.262 and USD \$ 0.319 for fire/explosion and grounding (drift), respectively. The NPV (total Δ B) with the ship lifecycle (40 years) and a depreciation rate of 5% is US \$ 0.000147. As a result, GCAF and NCAF calculated according to Equation (16) and (17) are US \$ 2.98 million and US \$ 2.93 million, respectively, indicating that the costs fall within the category of addressing the risk of life damage, as suggested by the IMO according to Table 7.

5. Discussion

5.1 Result of Fuzzy TOPSIS FMEA

According to Fig. 7 and Table 9, the risk rank could be classified into four groups according to the risk index through FMEA. Among them, 19 of hazards were included in the intolerable area, which had the highest risk index. However, the risk ranking of hazards included in the intolerable area can be specifically identified according to fuzzy TOPSIS FMEA. In addition, in FMEA, some hazards (hazard nos. 69, 70, 74, 75, 77, 86) included in the tolerable area had a higher risk ranking than some hazards (hazard nos. 31 and 42) included in the intolerable area. For various alternative fuel ships to be developed in the future, the three-step integrated risk assessment technique presented here can complement the subjectivity of the FMEA technique, while further refining the risk rating to identify critical hazards. As a result, it will be possible to specify hazards that require RCMs, thereby reducing the time to perform FSA.

5.2 Developed RCOs for critical hazards

As shown in Fig. 4, Step 3 of the FSA aims to propose a new effective and practical RCOs as a method to identify ways to control hazards. This study prepared a viable RCM by performing a risk assessment on LPG engine control systems to be installed on coastal ships and proposed safety standards through cost-benefit analysis. RCMs are prepared in consideration of identified major hazards and risk analysis results.

When combining RCMs with cost-benefit analysis, economic costs are expressed as lifecycle costs and include costs related to the initial investment, operation, education, inspection, certification, and decommission (IMO, 2007c). This can act as an element to prepare RCOs. In other words, in terms of education, it is possible to consider strengthening the training required when boarding qualified crewmembers owing to the operation of a new LPG fueled system as an RCO. This means including training separate from the basic training requirements defined by the IMO’s International Convention on Standards of Training, Certification and Watch keeping for Seafarers (STCW, 1978). In the case of seafarers on board ships using gases or other low-flashpoint ships, a special training course is required to familiarize them with their duties and responsibilities. Through this, it will be possible to prevent accidents caused by human factors.

To develop more reliable safety standards, future research is necessary to identify and evaluate more possible RCOs for all parts of LPG propulsion ships equipped with various LPG engine systems.

5.3 Cost-benefit assessment on developed RCO

In this study, fuzzy TOPSIS was applied as a risk assessment method in Step 2. Through this, the uncertainty of the traditional FMEA technique could be supplemented while easily and specifically selecting the main critical hazards. Thus, the periodic exchange of main critical hazards was presented as an RCM, and a cost-benefit analysis was performed. Here, the number of people on board the ship was considered to be 30. However, as the engine system is likely to be mounted on a coastal sailing ship, the actual number of people on board may be less than 30. In addition, the durability of government vessels is currently limited to 25 years in Korea. Accordingly, Fig. 9 shows a comparison of the results of the cost-benefit analysis considering variables such as a ship's lifespan and number of people on board.

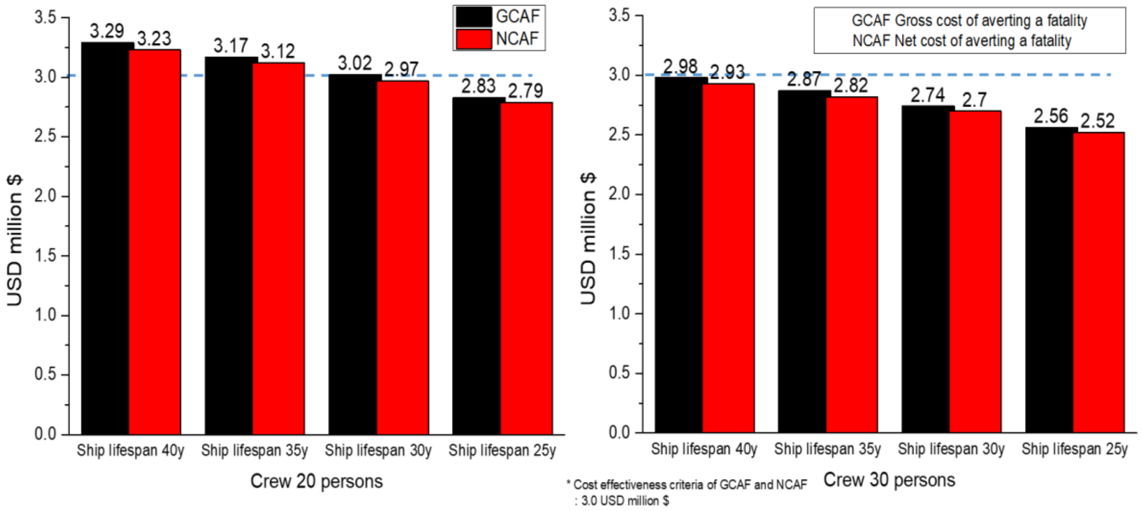


FIG. 9. Cost-benefit assessment based on various parameters.

In the case of 20 crew members and a ship lifespan of 40 years, the result of the cost-benefit assessment indicated that the presented RCO was not cost-effective. However, most of the items provided to ships were type-approved. If the interval of exchange for main critical hazards, which is an RCM proposed above, is extended from 5 to 10 years based on the reliability of the type-approved product, the GCAF and NCAF values are calculated as $2.01 million and US $1.96 million, respectively.

Therefore, safety standards within economic criteria can be established in consideration of various parameters.

In addition, the RCO (periodic exchange of critical hazards) developed through this study could be included in the safety requirements for coastal ships with the same type of LPG engine system when accepted as a domestic law following the revision of the IGF code.

5.4 Importance and prospects of the proposed novel FSA methodology

Safety standards are currently insufficient except for LNG among alternative fuels, and each alternative fuel contains risks such as toxicity and flammability (DNVGL, 2019). When ships that continuously use various alternative fuels are being built, particularly for alternative fuels with insufficient safety standards, risk-based design is crucial, and appropriate risk assessment techniques must be used for each design stage (IMO, 2013). At the seventh meeting of the IMO Carriage of Cargoes and Containers (CCC) in 2021, there was a report and discussion on the development status of the interim guidelines for the safety regulations for the construction and operation of LPG-fueled ships. South Korea has submitted the results of the HAZID study on LPG-fueled RoPax ship and supplemented draft guidelines for the construction and operation of LPG-fueled ships. Regarding the results of the HAZID study submitted by South Korea, some member countries emphasized the need for risk assessment for various types of vessels for the HAZID study, suggesting the requirement of identification of hazards and risk assessment based on the characteristics of LPG. Furthermore, the risk assessment of various techniques was suggested to be necessary owing to a lack of experience with LPG systems (IMO, 2021). As such, in order to verify the validity and safety of a new concept design or alternative design to which normative regulations and rules cannot be applied, risk assessment of various methods is required. Therefore, the three-step integrated risk assessment technique presented in this study can supplement the subjectivity of the FMEA technique that is a standard risk assessment technique, by fuzzy TOPSIS FMEA while further refining the risk ranking to identify critical hazards in detail for various alternative fuel ships that will be developed in the future. Furthermore, it is believed that the FSA technique will be widely used in analyzing the reduction of accidents and casualties and developing effective safety standards. In this study, the FMEA technique was applied to locally verify the reliability and safety of the LPG marine engine system in Step 1 of the three steps suggested. But, the HAZOP technique may also be applied to identify and evaluate possible hazards in the process and operation of the LPG engine system that can be applied to various facilities of the ship such as the fuel supply system and the loading and unloading system, in addition to the engine system. Through this, applying the technique developed in this study to alternative fuels that do not have safety regulations yet (except for LNG) will allow the establishment of safety regulations with improved reliability in a more time-efficient manner.

6. Conclusions

In this study, a risk assessment was conducted in three stages for the safety and accident prevention of the LPG marine engine system being developed for the first time in South Korea. Safety regulations were proposed for coastal vessels (particularly fishing vessels) with a high probability of being equipped with such an engine system. The following conclusions have been drawn from this study.

1) Conventional FMEA was performed by the expert group, and as a result, 89 hazards were identified. According to the result of the risk index that essentially represents the sum of the frequency and severity of each hazard, the risk ranks have been categorized into four groups.

2) For the 89 hazards identified through FMEA, five evaluation assessment criteria were applied to the three risk factors with the added detectability from the risk factors assessed by four experts via the FMEA method, and weights were assigned to the risk factors. In order to compensate for the subjectivity of FMEA, the fuzzy TOPSIS FMEA technique was applied. As a result, it was possible to precisely categorize the risk ranking into 28 groups.

3) Among the hazards selected through fuzzy TOPSIS FMEA, the high-ranking hazards were designated as the main critical hazards. The RCM was recommended to be a periodic exchange of main critical hazards according to the interval of the ship’s periodical survey (every 5 years). As a result of performing a cost-benefit analysis related to the implementation of the RCM according to the FSA technique, the cost-effectiveness criteria proposed by IMO were met (GCAF US $ 2.98 million and NCAF US $ 2.93 million).

4) The novel risk assessment technique proposed in this study is expected to become a new standard for FSA techniques because it balances the subjectivity of FMEA evaluation and effectively selects the major critical hazards that require safety measures based on the fuzzy TOPSIS FMEA technique, while reducing the time consumed by the FSA procedure.

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CRediT authorship contribution statement

Siljung Yeo: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing - original draft, Writing - review & editing. **Byongug Jeong:** Conceptualization, Resources, Supervision, Validation, Writing - review & editing. **Won-Ju Lee:** Supervision, Validation, Writing - review & editing, Funding acquisition.

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