

# SAFETY ASSESSMENT OF HYBRID PROPULSION SYSTEMS

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## ABSTRACT

With developing technology, power systems are improved too much in comparison with the past, including the marine industry. A hybrid propulsion system is gaining importance nowadays with its advantages, such as low noise, low fuel consumption, flexible power demand, volume, and weight and this system is safer, cleaner, and more comfortable. Although the optimistic appearance of the hybrid ship, there are still many unknowns and, in this way, unexpected risks and failures can be observed during operation. In this study, the effect of risk factors on the hybrid drive system has been investigated. For this purpose, Fuzzy Analytic Hierarchy Process (FAHP) is applied in the risk assessment of the hybrid system to identify risk factors. FAHP allows for the inclusion of subjective and uncertain judgments in the decision-making process by using fuzzy logic to deal with imprecise and vague information.

**Keywords:** Hybrid Propulsion System, Fuzzy Analytic Hierarchy Process, Safety Assessment.

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## 1. Introduction

At present, the effort of finding better, more economical, and more efficient systems and stricter emission regulations imposed by the International Maritime Organization (IMO) make engineers offer smart solutions.

A hybrid propulsion system includes a main diesel engine and an electric motor. Mechanic and electric power are working together and this provides a flexible power demand. The combination of the mechanical power provided by the diesel engines and the electrical power provided by the electric motors provides the propulsion power that gives the ship a wide range of operational capabilities and the right amount of power and torque to the propeller in each operating mode (Turbo, 2014). Switching from a diesel engine to an electric motor or reversing at the right time yields of fuel efficiency. For the diesel-mechanic system, the propulsion system is designed to maximize power demand but in a hybrid system, there is no such problem because of the flexible power demand capability (Barrett et al., 2009).

The propulsion system for merchant ships includes one slow-running diesel engine which connected directly mechanically, named the shaft system to the propeller. This system needs a large amount of space for a diesel engine or a shaft system. The space required for electric motors

is small compared to the diesel system. Differing from diesel driving, there is a diesel engine, coupled with electric motors, which is the main power source and there are electric motors are used for driving the propeller in a hybrid system (Examiner et al., 2007). In addition, the energy produced is stored in the marine hybrid propulsion systems. To store the energy, some systems are used in that propulsion system. Batteries, flywheels, and hydrogen fuels are can be examples of storage systems. The most common one is batteries (Mentes & Akyildiz, 2019). Also, another parameter that plays an important role in propulsion systems' hybridization; is pollution. Greenhouse gas emissions are very important and increasing day by day. If no action is taken, emissions will be much more in 2050 (Bennabi et al., 2016).

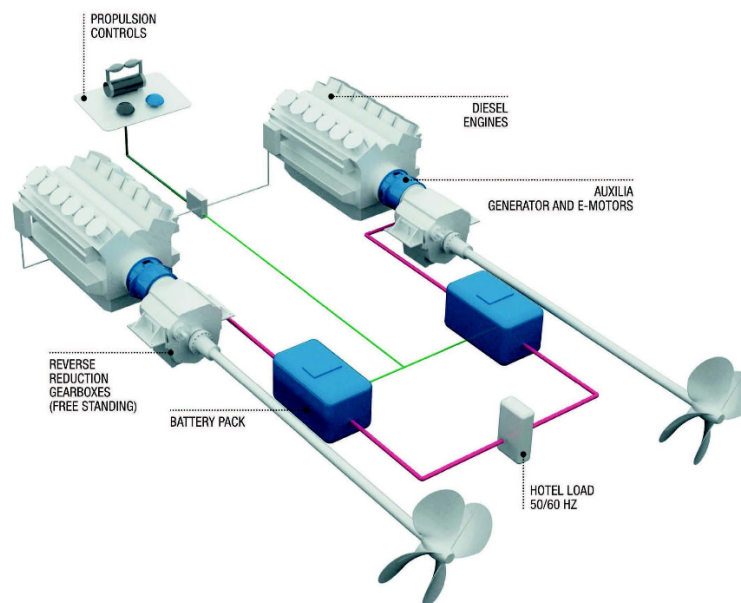
In most cases, decision-makers face a specific set of alternatives to choose from. This kind of decision-making problem is intuitive when considering a single criterion because experts can choose the alternative of the highest preference. It becomes complicated when there are multiple criteria. These criteria are often not of equal importance and alternatives have a wide range of performances. There is a need for useful methods to provide a structured method of decision-making. There are several multi-criteria decision-making methods, such as Analytic Hierarchy Process, Technique for Order Preference by Similarity to Ideal (TOPSIS), Functional Resonance Accident Method (FRAM), Bowtie, Fault Tree Analysis, Event Tree Analysis, Bayesian Approach, and Grey Theory, etc. These methods are used depending on the event or conditions and differ from each other with their unique properties.

Fuzzy set theory (FST) was first introduced by Zadeh and Klaua in 1965. A fuzzy set is a class of objects characterized by a membership function that assigns each object a membership degree ranging from 0 to 1. The theory is an important method, especially for measuring the uncertainty of concepts associated with subjective judgments of people, and using it in engineering, management, and medicine. Bellman and Zadeh (1970) were the first to associate FST with decision-making problems using uncertain data to make decisions. Yager and Basson (1975) used FST to decision-making problems (Mentes & Helvacioğlu, 2012).

The Analytical Hierarchy Process (AHP), developed by Thomas L. Saaty in the 1970s, is a method for organising and analysing complex decisions using mathematics and psychology. It comprises three parts: purpose or problem, alternatives, and criteria by which you evaluate alternatives. Quantification capability distinguishes AHP from other multi-criteria decision-making methods. AHP is most useful when deciding complex high-risk problems. It differs from other decision-making techniques because it measures criteria that are difficult to measure structuring complexity, measurement, and synthesis of the three primary AHP method functions (Tian & Yan, 2013). In the first function, it is necessary to identify all the different factors influencing the decision and to organize a hierarchical structure to deal with the complexity of the decision making process. The measurement on the ratio scale is attained by comparing these factors in pairs, and the relative importance numbers with nine levels are used in the comparison and finally finding the weights. However, binary comparison, which is the essence of AHP, can bring with it uncertainty as it requires the judgment of experts. In practical situations, decision-makers may not assign exact numerical values to their preferences due to limited knowledge or ability. There are six steps for this method: define the problem and determine the kind of knowledge sought, structure the decision hierarchy, construct matrices to calculate a set of pairwise comparisons, calculate the relative weight of the elements to each level, check and balance of decision and decision documentation (Russo & Camanho, 2015).

Fuzzy sets are combined with AHP, as subjective judgments at the time of comparison may be uncertain. This is called Fuzzy Analytic Hierarchy Process (FAHP). In a fuzzy environment, an analysis of hierarchical structures was proposed by Buckley (1985), who initially examined

decision-makers' statements regarding binary comparisons by using fuzzy ratios instead of crisp values. One of the most recent and popular approaches to the solution processes of the FAHP methodology is based on Chang's (1996) extent analysis. Chang's extent analysis is relatively straightforward when comparing other approaches to FAHP. Zhu et al. (1999) represented the key point of the extent analysis method and represented a discussion of the use of triangular fuzzy numbers in FAHP applications (Celik et al., 2009). To remove ambiguity in AHP, exact numbers are replaced with fuzzy numbers that represent linguistic expressions in fuzzy AHP. However, adding fuzzy sets to AHP makes the computation process more complex because different fuzzy sets are available. All of these decision problems are related to the evaluation and prioritization of alternatives, which may be physical entities or intangible items. The results are used for selection if a preferred solution is required. There are six steps for this method: structure the problem, establish the fuzzy pair-wise comparison matrix, synthesise the judgments, calculate the fuzzy weights of the criteria, defuzzify the fuzzy weights, and check the consistency (Liu et al., 2020).



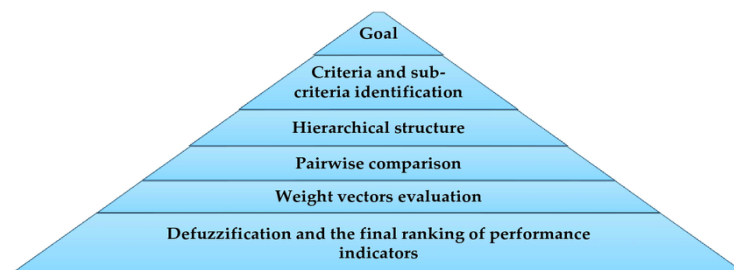
**Figure 1.** Hybrid propulsion system main elements (<https://www.auxilia-propulsion.com/index.php/news/a-new-marine-hybrid-kit>).

The main risk factors for the hybrid propulsion system can be divided into three primary parts because of the hybrid system elements: diesel engine, generator, and battery shown in Figure 1. Each of the main parts has complex engineering problems called sub-risks that come from articles and expert judgments, so there are a lot of criteria and sub-criteria that decision-makers have to decide which one is the most significant. For the diesel engine; fuel oil leakage, cooling water leakage, turbocharger mechanical failure, air cooler problems, fuel oil pump failures, and oil pressure (Alarcin et al., 2014). For the generator; overheating between moving parts, cooling water pump failure, leakage from pipings, failure of alarms, water leaking in oil, and over speed because of the expert judgments. For the battery; need more power than the power obtained from the battery, malfunction in the energy management system, battery short circuit, overheating and fire in the battery, physical contact of the battery with water, and sudden amperage or voltage increases (Mentes & Akyildiz, 2019).

In the current study, the FAHP method helps decision-makers with the inclusion of subjective and uncertain judgments in the decision-making process by using fuzzy logic to deal with imprecise and vague information.

## 2. Fuzzy AHP Method

The steps of the fuzzy analytic hierarchy process are generally defined as the goal, identifying the criteria and sub-criteria, making a hierarchical structure, preparing the pair-wise comparison matrix, evaluating the weight vectors and, finally defuzzification and the final ranking of performance indicators like in Figure 2.



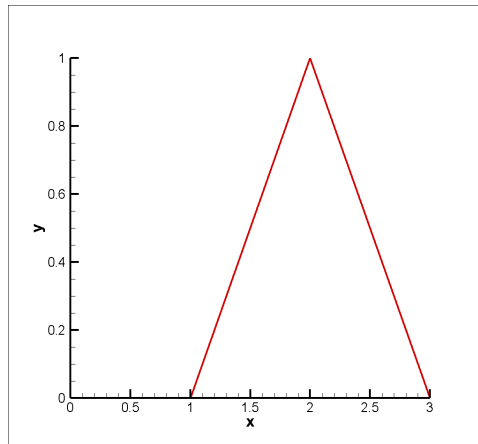
**Figure 2.** Steps of FAHP.

After defining the goal, identifying the criteria and sub-criteria, making a hierarchical structure, preparing the pair-wise comparison matrix comes for comparing the criteria with each other. First, a pair-wise comparison matrix with crisp values is prepared and crisp values are used (Table 1).

**Table 1.** Relative importance numbers.

<b>Fuzzy Scale of Relative Importance</b>	
Equal	1
Intermediate Value	2
Moderate	3
Intermediate Value	4
Strong	5
Intermediate Value	6
Very Strong	7
Intermediate Value	8
Extremely Strong	9

However, crisp values should not be used in FAHP method, so when preparing the pair-wise comparison matrix, to make the crisp value fuzzy number, membership function must be used. There are some membership functions, such as triangular membership function and trapezoidal membership function. In this study, the triangular membership function was used in which  $\mu_A(x) = (1,2,3)$  is a fuzzy number coming from triangular membership function (Figure 3). '1' means the lower number, '2' is the middle number and '3' is the upper number here.



**Figure 3.** Fuzzification based on triangular membership function.

In Table 2, the transformed fuzzy number based on the triangular membership function is given and the number will be used in a pair-wise comparison matrix.

**Table 2.** Fuzzy relative importance numbers.

<b>Fuzzy Scale of Relative Importance</b>	
Equal	(1,1,1)
Intermediate Value	(1,2,3)
Moderate	(2,3,4)
Intermediate Value	(3,4,5)
Strong	(4,5,6)
Intermediate Value	(5,6,7)
Very Strong	(6,7,8)
Intermediate Value	(7,8,9)
Extremely Strong	(9,9,9)

After preparing the pair-wise comparison matrix, the weight vectors have been evaluated. Then, Eq. (1) is used to calculate the weight factors:

$$SI = \sum_{j=1}^n a_{ij} \left[ \sum_{i=1}^n \sum_{j=1}^n a_{ij} \right]^{-1} \quad (1)$$

First, the fuzzy numbers which in each row should be summed to obtain total fuzzy numbers. Then, total fuzzy numbers should be summed and thereafter obtained the one final fuzzy number. The summation for fuzzy numbers will be as follows:

$$A_1 \oplus A_2 = (l_1, m_1, u_1) \oplus (l_2, m_2, u_2) = (l_1 + l_2, m_1 + m_2, u_1 + u_2) \quad (2)$$

After the finding total and final fuzzy number, the inverse of the final fuzzy number should be taken using the following formula:

$$(l, m, u)^{-1} = \left( \frac{1}{u}, \frac{1}{m}, \frac{1}{l} \right) \quad (3)$$

Then, there are two fuzzy number multiplication steps to obtain the weight vectors in the following formula:

$$A_1 \otimes A_2 = (l_1, m_1, u_1) \otimes (l_2, m_2, u_2) = (l_1 * l_2, m_1 * m_2, u_1 * u_2) \quad (4)$$

Finally, in the step of defuzzification and finding the final ranking of performance indicators, the degree of possibilities should be calculated.

$$\begin{aligned} & 1.5 \text{ if } m_1 \geq m_2 \\ & 0.5 \text{ if } l_2 \geq u_1 \\ & \frac{l_2 - u_1}{(m_1 - u_1) - (m_2 - l_2)} + 0.5 \text{ if otherwise} \end{aligned} \quad (5)$$

The minimum value in possibilities for each S value should be taken and normalised.

$$V(S \geq S_1, S_2, \dots, S_K) = \min V(S \geq S_I), \quad I = 1, 2, \dots, K \quad (6)$$

$$d'(A_I) = \min V(S_I \geq S_K), \quad I, K = 1, 2, \dots, N; \quad K \neq I$$

$$W' = (d'(A_1), d'(A_2), \dots, d'(A_N))^T \quad (7)$$

### 3. Safety Assessment

#### 3.1. Criteria and Sub-Criteria Identification

To make a safety assessment with FAHP, it is necessary to define the goal first for determining the risks of the hybrid propulsion system. Risks or failure types can be divided into three categories according to hybrid system elements:

1. F<sub>1</sub>: Diesel engine failures
2. F<sub>2</sub>: Generator failures
3. F<sub>3</sub>: Battery failures

Each category has also six sub-categories. The critical risks in diesel engines are:

- f<sub>11</sub>: Fuel oil leakage
- f<sub>12</sub>: Cooling water leakage
- f<sub>13</sub>: Turbocharger mechanical failure
- f<sub>14</sub>: Air cooler problem
- f<sub>15</sub>: Fuel oil pump failures
- f<sub>16</sub>: Oil pressure

The critical risks in the generators are:

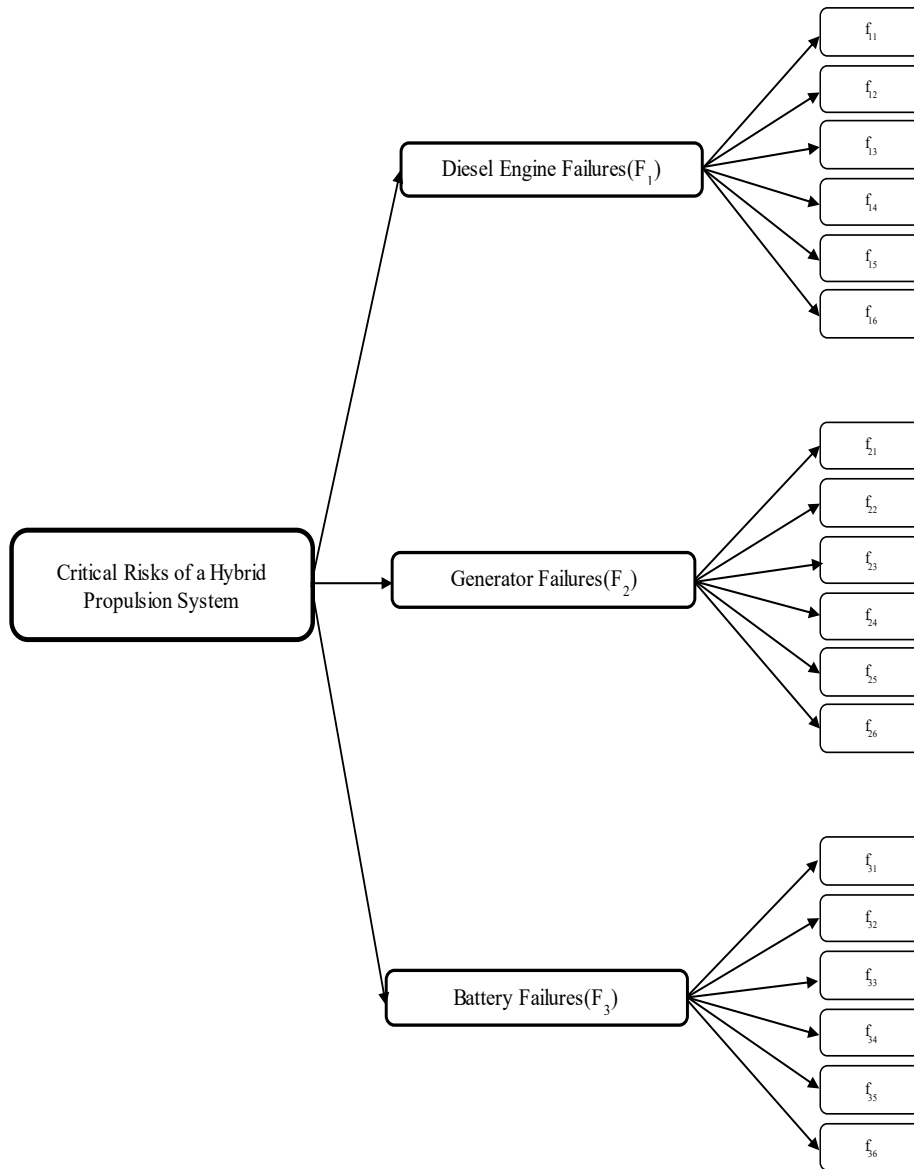
- f<sub>21</sub>: Overheating between moving parts
- f<sub>22</sub>: Cooling water pumps failure
- f<sub>23</sub>: Leakage from pipings
- f<sub>24</sub>: Failure of alarms
- f<sub>25</sub>: Water leaking in oil
- f<sub>26</sub>: Overspeed

The critical risks in the batteries are:

- f<sub>31</sub>: Need more power than the power obtained from the battery
- f<sub>32</sub>: Malfunction in the energy management system
- f<sub>33</sub>: Battery short circuit

- $f_{34}$  : Overheating and fire in the battery
- $f_{35}$  : Physical contact of the battery with water
- $f_{36}$  : Sudden amperage or voltage increases

### 3.2 Hierarchical Structure



**Figure 4.** The hierarchical structure of the hybrid propulsion system risk assessment.

### 3.3. Pair-wise Comparison

#### *i. Diesel Engine*

Pair-wise comparison matrix with crisp values for the six diesel engine failure types is given in Table 3.

**Table 3.** Pair-wise comparison with crisp numbers for diesel engine failures.

SC	$f_{11}$	$f_{12}$	$f_{13}$	$f_{14}$	$f_{15}$	$f_{16}$
$f_{11}$	1	3	7	5	6	9
$f_{12}$	1/3	1	5	3	4	6
$f_{13}$	1/7	1/5	1	1/3	1/2	3
$f_{14}$	1/5	1/3	3	1	2	5
$f_{15}$	1/6	1/4	2	1/2	1	4
$f_{16}$	1/9	1/6	1/3	1/5	1/4	1

Pair-wise comparison matrix with fuzzy numbers for the six diesel engine failure types is shown in Table 4.

**Table 4.** Pair-wise comparison with fuzzy numbers for diesel engine failures.

SC	$f_{11}$	$f_{12}$	$f_{13}$	$f_{14}$	$f_{15}$	$f_{16}$
$f_{11}$	(1,1,1)	(2,3,4)	(6,7,8)	(4,5,6)	(5,6,7)	(9,9,9)
$f_{12}$	(1/4,1/3,1/2)	(1,1,1)	(4,5,6)	(2,3,4)	(3,4,5)	(5,6,7)
$f_{13}$	(1/8,1/7,1/6)	(1/6,1/5,1/4)	(1,1,1)	(1/4,1/3,1/2)	(1/3,1/2,1/1)	(2,3,4)
$f_{14}$	(1/6,1/5,1/4)	(1/4,1/3,1/2)	(2,3,4)	(1,1,1)	(1,2,3)	(4,5,6)
$f_{15}$	(1/7,1/6,1/5)	(1/5,1/4,1/3)	(1,2,3)	(1/3,1/2,1/1)	(1,1,1)	(3,4,5)
$f_{16}$	(1/9,1/9,1/9)	(1/7,1/6,1/5)	(1/4,1/3,1/2)	(1/6,1/5,1/4)	(1/5,1/4,1/3)	(1,1,1)

#### *ii. Generator*

Pair-wise comparison matrix with crisp values for the six generator failure types is given in Table 5.

**Table 5.** Pair-wise comparison with crisp numbers for generator failures.

SC	$f_{21}$	$f_{22}$	$f_{23}$	$f_{24}$	$f_{25}$	$f_{26}$
$f_{21}$	1	1/2	2	2	3	1/2
$f_{22}$	2	1	3	5	4	2
$f_{23}$	1/2	1/3	1	2	3	1/3
$f_{24}$	1/2	1/5	1/2	1	2	1/4
$f_{25}$	1/3	1/4	1/3	1/2	1	1/3
$f_{26}$	2	1/2	3	4	3	1

Pair-wise comparison matrix with fuzzy numbers for the six generator failure types is shown in Table 6.

**Table 6.** Pair-wise comparison with fuzzy numbers for generator failures.

SC	$f_{21}$	$f_{22}$	$f_{23}$	$f_{24}$	$f_{25}$	$f_{26}$
$f_{21}$	(1,1,1)	(1/3,1/2,1/1)	(1,2,3)	(1,2,3)	(2,3,4)	(1/3,1/2,1/1)
$f_{22}$	(1,2,3)	(1,1,1)	(2,3,4)	(4,5,6)	(3,4,5)	(1,2,3)
$f_{23}$	(1/3,1/2,1/1)	(1/4,1/3,1/2)	(1,1,1)	(1,2,3)	(2,3,4)	(1/4,1/3,1/2)
$f_{24}$	(1/3,1/2,1/1)	(1/6,1/5,1/4)	(1/3,1/2,1/1)	(1,1,1)	(1,2,3)	(1/5,1/4,1/3)
$f_{25}$	(1/4,1/3,1/2)	(1/5,1/4,1/3)	(1/4,1/3,1/2)	(1/3,1/2,1/1)	(1,1,1)	(1/4,1/3,1/2)
$f_{26}$	(1,2,3)	(1/3,1/2,1/1)	(2,3,4)	(3,4,5)	(2,3,4)	(1,1,1)

### iii. Battery

Pair-wise comparison matrix with crisp values for the six battery failure types is given in Table 7.

**Table 7.** Pair-wise comparison with crisp numbers for battery failures.

SC	$f_{31}$	$f_{32}$	$f_{33}$	$f_{34}$	$f_{35}$	$f_{36}$
$f_{31}$	1	1/4	1/5	1/7	1/2	1/3
$f_{32}$	4	1	1/2	1/4	3	2
$f_{33}$	5	2	1	1/3	4	3
$f_{34}$	7	4	3	1	6	5
$f_{35}$	2	1/3	1/4	1/6	1	1/2
$f_{36}$	3	1/2	1/3	1/5	2	1

Pair-wise comparison matrix with fuzzy numbers for the six battery failure types shown in Table 8.

**Table 8.** Pair-wise comparison with fuzzy numbers for battery failures.

SC	$f_{31}$	$f_{32}$	$f_{33}$	$f_{34}$	$f_{35}$	$f_{36}$
$f_{31}$	(1,1,1)	(1/5,1/4,1/3)	(1/6,1/5,1/4)	(1/8,1/7,1/6)	(1/3,1/2,1/1)	(1/4,1/3,1/2)
$f_{32}$	(3,4,5)	(1,1,1)	(1/3,1/2,1/1)	(1/5,1/4,1/3)	(2,3,4)	(1,2,3)
$f_{33}$	(4,5,6)	(1,2,3)	(1,1,1)	(1/4,1/3,1/2)	(3,4,5)	(2,3,4)
$f_{34}$	(6,7,8)	(3,4,5)	(2,3,4)	(1,1,1)	(5,6,7)	(4,5,6)
$f_{35}$	(1,2,3)	(1/4,1/3,1/2)	(1/5,1/4,1/3)	(1/7,1/6,1/5)	(1,1,1)	(1/3,1/2,1/1)
$f_{36}$	(2,3,4)	(1/3,1/2,1/1)	(1/4,1/3,1/2)	(1/6,1/5,1/4)	(1,2,3)	(1,1,1)

## 3.4. Weight Vectors Evaluation

The weights are calculated for the sub-criteria of diesel engine, generator, and battery by using Eq. (1).

### i. Diesel Engine

Fuzzified relative importance numbers in the rows are summed using formula (2) and get total numbers for diesel engine failures. Then, total fuzzy numbers are summed using formula (2) and get the final fuzzy number given in Table 9.

**Table 9.** Summing the fuzzy numbers step for diesel engine failures.

SC	f <sub>11</sub>	f <sub>12</sub>	f <sub>13</sub>	f <sub>14</sub>	f <sub>15</sub>	f <sub>16</sub>	Total
f <sub>11</sub>	(1,1,1)	(2,3,4)	(6,7,8)	(4,5,6)	(5,6,7)	(9,9,9)	(27,31,35)
f <sub>12</sub>	(1/4,1/3,1/2)	(1,1,1)	(4,5,6)	(2,3,4)	(3,4,5)	(5,6,7)	(15.3,19.3,23.5)
f <sub>13</sub>	(1/8,1/7,1/6)	(1/6,1/5,1/4)	(1,1,1)	(1/4,1/3,1/2)	(1/3,1/2,1/1)	(2,3,4)	(3.9,5.2,6.9)
f <sub>14</sub>	(1/6,1/5,1/4)	(1/4,1/3,1/2)	(2,3,4)	(1,1,1)	(1,2,3)	(4,5,6)	(8.4,11.5,14.8)
f <sub>15</sub>	(1/7,1/6,1/5)	(1/5,1/4,1/3)	(1,2,3)	(1/3,1/2,1/1)	(1,1,1)	(3,4,5)	(5.7,7.9,10.5)
f <sub>16</sub>	(1/9,1/9,1/9)	(1/7,1/6,1/5)	(1/4,1/3,1/2)	(1/6,1/5,1/4)	(1/5,1/4,1/3)	(1,1,1)	(1.9,2.2,2.4)
							(62.1,77.0,93.1)

After that, multiply the total fuzzy numbers using formula (4) with the inverse of the final fuzzy number using formula (3) for diesel engine failures given in Table 10.

**Table 10.** Multiplication of the fuzzy numbers for diesel engine failures.

SC	Total	Multiplication	Weight Vector
f <sub>11</sub>	(27,31,35)	(27,31,35)x(1/93.09,1/77.02,1/62.08)	(0.290,0.402,0.563)
f <sub>12</sub>	(15.25,19.33,23.50)	(15.25,19.33,23.50)x(1/93.09,1/77.02,1/62.08)	(0.163,0.251,0.378)
f <sub>13</sub>	(3.87,5.17,6.91)	(3.87,5.17,6.91)x(1/93.09,1/77.02,1/62.08)	(0.041,0.067,0.111)
f <sub>14</sub>	(8.41,11.53,14.75)	(8.41,11.53,14.75)x(1/93.09,1/77.02,1/62.08)	(0.090,0.149,0.237)
f <sub>15</sub>	(5.67,7.91,10.53)	(5.67,7.91,10.53)x(1/93.09,1/77.02,1/62.08)	(0.061,0.102,0.169)
f <sub>16</sub>	(1.87,2.06,2.39)	(1.87,2.06,2.39)x(1/93.09,1/77.02,1/62.08)	(0.020,0.026,0.038)

**ii. Generator**

Fuzzified relative importance numbers in the rows are summed using formula (2) and get total numbers for generator failures. Then, total fuzzy numbers are summed using formula (2) and get the final fuzzy number given in Table 11.

**Table 11.** Summing the fuzzy numbers step for generator failures.

SC	f <sub>21</sub>	f <sub>22</sub>	f <sub>23</sub>	f <sub>24</sub>	f <sub>25</sub>	f <sub>26</sub>	Total
f <sub>21</sub>	(1,1,1)	(1/3,1/2,1/1)	(1,2,3)	(1,2,3)	(2,3,4)	(1/3,1/2,1/1)	(5.66,9,13)
f <sub>22</sub>	(1,2,3)	(1,1,1)	(2,3,4)	(4,5,6)	(3,4,5)	(1,2,3)	(12,17,22)
f <sub>23</sub>	(1/3,1/2,1/1)	(1/4,1/3,1/2)	(1,1,1)	(1,2,3)	(2,3,4)	(1/4,1/3,1/2)	(4.83,7.16,10)
f <sub>24</sub>	(1/3,1/2,1/1)	(1/6,1/5,1/4)	(1/3,1/2,1/1)	(1,1,1)	(1,2,3)	(1/5,1/4,1/3)	(3.03,4.45,6.58)
f <sub>25</sub>	(1/4,1/3,1/2)	(1/5,1/4,1/3)	(1/4,1/3,1/2)	(1/3,1/2,1/1)	(1,1,1)	(1/4,1/3,1/2)	(2.28,2.75,3.83)
f <sub>26</sub>	(1,2,3)	(1/3,1/2,1/1)	(2,3,4)	(3,4,5)	(2,3,4)	(1,1,1)	(9.33,13.5,18)
							(37.15,53.86,73.41)

After that, multiply the total fuzzy numbers using formula (4) with the inverse of the final fuzzy number using formula (3) for generator failures given in Table 12.

**Table 12.** Multiplication of the fuzzy numbers for generator failures.

SC	Total	Multiplication	Weight Vector
f <sub>21</sub>	(5.66,9,13)	(5.66,9,13)x(1/73.41,1/53.86,1/37.15)	(0.077,0.167,0.350)
f <sub>22</sub>	(12,17,22)	(12,17,22) x(1/73.41,1/53.86,1/37.15)	(0.163,0.316,0.592)
f <sub>23</sub>	(4.83,7.16,10)	(4.83,7.16,10) x(1/73.41,1/53.86,1/37.15)	(0.066,0.133,0.269)
f <sub>24</sub>	(3.03,4.45,6.58)	(3.03,4.45,6.58) x(1/73.41,1/53.86,1/37.15)	(0.041,0.083,0.177)
f <sub>25</sub>	(2.28,2.75,3.83)	(2.28,2.75,3.83) x(1/73.41,1/53.86,1/37.15)	(0.031,0.051,0.103)
f <sub>26</sub>	(9.33,13.5,18)	(9.33,13.5,18) x(1/73.41,1/53.86,1/37.15)	(0.127,0.251,0.485)

**iii. Battery**

Fuzzified relative importance numbers in the rows are summed using formula (2) and get total numbers for battery failures. Then, total fuzzy numbers are summed using formula (2) and get the final fuzzy number given in Table 13.

**Table 13.** Summing the fuzzy numbers step for battery failures.

SC	f <sub>31</sub>	f <sub>32</sub>	f <sub>33</sub>	f <sub>34</sub>	f <sub>35</sub>	f <sub>36</sub>	Total
f <sub>31</sub>	(1,1,1)	(1/5,1/4,1/3)	(1/6,1/5,1/4)	(1/8,1/7,1/6)	(1/3,1/2,1/1)	(1/4,1/3,1/2)	(2.07,2.42,3.25)
f <sub>32</sub>	(3,4,5)	(1,1,1)	(1/3,1/2,1/1)	(1/5,1/4,1/3)	(2,3,4)	(1,2,3)	(7.53,10.75,14.33)
f <sub>33</sub>	(4,5,6)	(1,2,3)	(1,1,1)	(1/4,1/3,1/2)	(3,4,5)	(2,3,4)	(11.25,15.33,19.5)
f <sub>34</sub>	(6,7,8)	(3,4,5)	(2,3,4)	(1,1,1)	(5,6,7)	(4,5,6)	(21,26,31)
f <sub>35</sub>	(1,2,3)	(1/4,1/3,1/2)	(1/5,1/4,1/3)	(1/7,1/6,1/5)	(1,1,1)	(1/3,1/2,1/1)	(2.92,4.25,6.03)
f <sub>36</sub>	(2,3,4)	(1/3,1/2,1/1)	(1/4,1/3,1/2)	(1/6,1/5,1/4)	(1,2,3)	(1,1,1)	(4.75,7.03,9.75)
							(49.53,65.79,83.86)

After that, multiply the total fuzzy numbers using formula (4) with the inverse of the final fuzzy number using formula (3) for battery failures given in Table 14.

**Table 14.** Multiplication of the fuzzy numbers for battery failures.

SC	Total	Multiplication	Weight Vector
f <sub>31</sub>	(2.07,2.42,3.25)	(2.07,2.42,3.25)x(1/83.86,1/65.79,1/49.53)	(0.024,0.036,0.065)
f <sub>32</sub>	(7.53,10.75,14.33)	(7.53,10.75,14.33)x(1/83.86,1/65.79,1/49.53)	(0.089,0.163,0.289)
f <sub>33</sub>	(11.25,15.33,19.5)	(11.25,15.33,19.5)x(1/83.86,1/65.79,1/49.53)	(0.134,0.233,0.393)
f <sub>34</sub>	(21,26,31)	(21,26,31)x(1/83.86,1/65.79,1/49.53)	(0.250,0.395,0.625)
f <sub>35</sub>	(2.92,4.25,6.03)	(2.92,4.25,6.03)x(1/83.86,1/65.79,1/49.53)	(0.034,0.064,0.121)
f <sub>36</sub>	(4.75,7.03,9.75)	(4.75,7.03,9.75)x(1/83.86,1/65.79,1/49.53)	(0.056,0.106,0.196)

**3.5. Defuzzification and Final Ranking of Performance Indicators**

**i. Diesel Engine**

Weight vectors are shown for each sub-criterion of diesel engine failures in Table 15.

**Table 15.** Weight vectors for diesel engine failures.

Sub-Criteria (SC)	SI	Final
f <sub>11</sub>	S1	(0.290,0.402,0.563)
f <sub>12</sub>	S2	(0.163,0.251,0.378)
f <sub>13</sub>	S3	(0.041,0.067,0.111)
f <sub>14</sub>	S4	(0.090,0.149,0.237)
f <sub>15</sub>	S5	(0.061,0.102,0.169)
f <sub>16</sub>	S6	(0.020,0.026,0.038)

Degree of possibilities for each sub-criterion of diesel engine should be calculated by using the formula (5).

$$\begin{aligned}
 V(S1 \geq S2) &= 0.500 & V(S2 \geq S1) &= 0.869 & V(S3 \geq S1) &= 0.500 \\
 V(S1 \geq S3) &= 1.500 & V(S2 \geq S3) &= 1.500 & V(S3 \geq S2) &= 0.500 \\
 V(S1 \geq S4) &= 1.500 & V(S2 \geq S4) &= 1.500 & V(S3 \geq S4) &= 0.703 \\
 V(S1 \geq S5) &= 1.500 & V(S2 \geq S5) &= 1.500 & V(S3 \geq S5) &= 1.086 \\
 V(S1 \geq S6) &= 1.500 & V(S2 \geq S6) &= 1.500 & V(S3 \geq S6) &= 1.500 \\
 V(S4 \geq S1) &= 0.500 & V(S5 \geq S1) &= 0.500 & V(S6 \geq S1) &= 0.500 \\
 \\
 V(S4 \geq S2) &= 0.921 & V(S5 \geq S2) &= 0.538 & V(S6 \geq S2) &= 0.500 \\
 V(S4 \geq S3) &= 1.500 & V(S5 \geq S3) &= 1.500 & V(S6 \geq S3) &= 0.500 \\
 V(S4 \geq S5) &= 1.500 & V(S5 \geq S4) &= 1.128 & V(S6 \geq S4) &= 0.500 \\
 V(S4 \geq S6) &= 1.500 & V(S5 \geq S6) &= 1.500 & V(S6 \geq S5) &= 0.500
 \end{aligned}$$

After this step, the minimum possibilities should be taken for diesel engine failures with using formula (6).

$$\begin{aligned}
 V(S1 \geq S2, S3, S4, S5, S6) &= 1.500 & V(S2 \geq S1, S3, S4, S5, S6) &= 0.869 \\
 V(S3 \geq S1, S2, S4, S5, S6) &= 0.500 & V(S4 \geq S1, S2, S3, S5, S6) &= 0.500 \\
 V(S5 \geq S1, S2, S3, S4, S6) &= 0.500 & V(S6 \geq S1, S2, S3, S4, S5) &= 0.500
 \end{aligned}$$

Finally, to find the weights of the diesel engine by using the formula (7), the final weights of the diesel engine sub-criteria are shown in Table 16.

$$\begin{aligned}
 W' &= [(1.500, 0.869, 0.500, 0.500, 0.500, 0.500)]^T \text{ normalized like:} \\
 &= [(1.500/4.369, 0.869/4.369, 0.500/4.369, 0.500/4.369, 0.500/4.369, 0.500/4.369)]^T \\
 &= [(0.343, 0.198, 0.114, 0.114, 0.114, 0.114)]^T
 \end{aligned}$$

**Table 16.** Weights for each sub-criteria for diesel engine failures.

Sub-Criteria (SC)	Weight
$f_{11}$	0.343
$f_{12}$	0.198
$f_{13}$	0.114
$f_{14}$	0.114
$f_{15}$	0.114
$f_{16}$	0.114

Finally;

- $f_{11}$  which is the fuel oil leakage has a 34.3%
- $f_{12}$  which is the cooling water leakage has a 19.8%
- $f_{13}$  which is the turbocharger mechanical failure, has an 11.4%
- $f_{14}$  which is the air cooler problem, has an 11.4%
- $f_{15}$  which is the fuel oil pump failure, has an 11.4%
- $f_{16}$  which is the oil pressure, has an 11.4% importance degree for the diesel engine failures in the marine hybrid propulsion systems.

**ii. Generator**

Weight vectors are shown for each sub-criteria for generator failures in Table 17.

**Table 17.** Weight vectors for generator failures.

Sub-Criteria (SC)	SI	Final
$f_{21}$	S1	(0.077,0.167,0.350)
$f_{22}$	S2	(0.163,0.316,0.592)
$f_{23}$	S3	(0.066,0.133,0.269)
$f_{24}$	S4	(0.041,0.083,0.177)
$f_{25}$	S5	(0.031,0.051,0.103)
$f_{26}$	S6	(0.127,0.251,0.485)

Then, degree of possibilities for each sub-criterion of the generator should be calculated by using the formula (5).

$V(S1 \geq S2) = 1.057$	$V(S2 \geq S1) = 1.500$	$V(S3 \geq S1) = 1.349$
$V(S1 \geq S3) = 1.500$	$V(S2 \geq S3) = 1.500$	$V(S3 \geq S2) = 0.867$
$V(S1 \geq S4) = 1.500$	$V(S2 \geq S4) = 1.500$	$V(S3 \geq S4) = 1.500$
$V(S1 \geq S5) = 1.500$	$V(S2 \geq S5) = 1.500$	$V(S3 \geq S5) = 1.500$
$V(S1 \geq S6) = 1.227$	$V(S2 \geq S6) = 1.500$	$V(S3 \geq S6) = 1.047$
$V(S4 \geq S1) = 1.042$	$V(S5 \geq S1) = 0.683$	$V(S6 \geq S1) = 1.500$
$V(S4 \geq S2) = 0.556$	$V(S5 \geq S2) = 0.500$	$V(S6 \geq S2) = 1.332$
$V(S4 \geq S3) = 1.188$	$V(S5 \geq S3) = 0.813$	$V(S6 \geq S3) = 1.500$
$V(S4 \geq S5) = 1.500$	$V(S5 \geq S4) = 1.162$	$V(S6 \geq S4) = 1.500$
$V(S4 \geq S6) = 0.730$	$V(S5 \geq S6) = 0.500$	$V(S6 \geq S5) = 1.500$

Then, the minimum degree of possibilities should be taken for generator failures with formula (6).

$V(S1 \geq S2, S3, S4, S5, S6) = 1.057$	$V(S2 \geq S1, S3, S4, S5, S6) = 1.500$
$V(S3 \geq S1, S2, S4, S5, S6) = 0.867$	$V(S4 \geq S1, S2, S3, S5, S6) = 0.556$
$V(S5 \geq S1, S2, S3, S4, S6) = 0.500$	$V(S6 \geq S1, S2, S3, S4, S5) = 1.332$

Finally, to find the weights of the generator by using the formula (7), the final weights of the generator sub-criteria are shown in Table 18.

$$\begin{aligned}
 W' &= [(1.057, 1.500, 0.867, 0.556, 0.500, 1.332)]^T \text{ normalized like:} \\
 &= [(1.057/5.812, 1.500/5.812, 0.867/5.812, 0.556/5.812, 0.500/5.812, 1.332/5.812)]^T \\
 &= [(0.181, 0.258, 0.149, 0.095, 0.086, 0.229)]^T
 \end{aligned}$$

**Table 18.** Weights for each sub-criteria for generator failures.

Sub-Criteria (SC)	Weight
$f_{21}$	0.181
$f_{22}$	0.258
$f_{23}$	0.149
$f_{24}$	0.095
$f_{25}$	0.086
$f_{26}$	0.229

Finally;

- $f_{21}$  which is the overheating between moving parts, has an 18.1%
- $f_{22}$  which is the cooling water pump failure, has a 25.8%
- $f_{23}$  which is the leakage from piping, has a 14.9%
- $f_{24}$  which is the failure of alarm, has a 9.50%
- $f_{25}$  which is the water leaking in oil, has an 8.60%
- $f_{26}$  which is the over-speed has a 22.9% importance degree for the generator failures in the marine hybrid propulsion systems.

### iii. Battery

Weight vectors are shown for each sub-criteria for battery failures in Table 19.

**Table 19.** Weight vectors for battery failures.

Sub-Criteria (SC)	SI	Final
$f_{31}$	S1	(0.024,0.036,0.065)
$f_{32}$	S2	(0.089,0.163,0.289)
$f_{33}$	S3	(0.134,0.233,0.393)
$f_{34}$	S4	(0.250,0.395,0.625)
$f_{35}$	S5	(0.034,0.064,0.121)
$f_{36}$	S6	(0.056,0.106,0.196)

Then, the degree of possibilities 's each sub-criteria battery should be calculated by using the formula (5).

$$V(S1 \geq S2) = 0.500$$

$$V(S1 \geq S3) = 0.500$$

$$V(S1 \geq S4) = 0.500$$

$$V(S1 \geq S5) = 1.025$$

$$V(S1 \geq S6) = 0.614$$

$$V(S4 \geq S1) = 1.500$$

$$V(S4 \geq S2) = 1.500$$

$$V(S4 \geq S3) = 1.500$$

$$V(S4 \geq S5) = 1.500$$

$$V(S4 \geq S6) = 1.500$$

$$V(S2 \geq S1) = 1.500$$

$$V(S2 \geq S3) = 1.189$$

$$V(S2 \geq S4) = 0.644$$

$$V(S2 \geq S5) = 1.500$$

$$V(S2 \geq S6) = 1.500$$

$$V(S5 \geq S1) = 1.500$$

$$V(S5 \geq S2) = 0.744$$

$$V(S5 \geq S3) = 0.500$$

$$V(S5 \geq S4) = 0.500$$

$$V(S5 \geq S6) = 1.107$$

$$V(S3 \geq S1) = 1.500$$

$$V(S3 \geq S2) = 1.500$$

$$V(S3 \geq S4) = 0.969$$

$$V(S3 \geq S5) = 1.500$$

$$V(S3 \geq S6) = 1.500$$

$$V(S6 \geq S1) = 1.500$$

$$V(S6 \geq S2) = 1.152$$

$$V(S6 \geq S3) = 0.828$$

$$V(S6 \geq S4) = 0.500$$

$$V(S6 \geq S5) = 1.500$$

After this step, the minimum degree of possibility should be taken for battery failures by using the formula (6).

$$\begin{aligned}
 V(S1 \geq S2, S3, S4, S5, S6) &= 0.500 & V(S2 \geq S1, S3, S4, S5, S6) &= 0.644 \\
 V(S3 \geq S1, S2, S4, S5, S6) &= 0.969 & V(S4 \geq S1, S2, S3, S5, S6) &= 1.500 \\
 V(S5 \geq S1, S2, S3, S4, S6) &= 0.500 & V(S6 \geq S1, S2, S3, S4, S5) &= 0.500
 \end{aligned}$$

Finally, to find the weights of the battery by using the formula (7), the final weights of the battery sub-criteria are shown in Table 20.

$$\begin{aligned}
 W' &= [(0.500, 0.644, 0.969, 1.500, 0.500, 0.500)]^T \text{ normalized like:} \\
 &= [(0.500/4.613, 0.644/4.613, 0.969/4.613, 1.500/4.613, 0.500/4.613, 0.500/4.613)]^T \\
 &= [(0.108, 0.139, 0.210, 0.325, 0.108, 0.108)]^T
 \end{aligned}$$

**Table 20.** Weights for each sub-criteria for battery failures.

Sub-Criteria (SC)	Weight
$f_{31}$	0.108
$f_{32}$	0.139
$f_{33}$	0.210
$f_{34}$	0.325
$f_{35}$	0.108
$f_{36}$	0.108

Finally;

- $f_{31}$  which is the need for more power than the power obtained from the battery parts has a 10.8%
- $f_{32}$  which is the malfunction in the energy management system, has a 13.9%
- $f_{33}$  which is the battery short circuit, has a 21.0%
- $f_{34}$  which is the overheating and fire in the battery, has a 32.5%
- $f_{35}$  which is the physical contact of the battery with water, has a 10.8%
- $f_{36}$  which is the sudden amperage or voltage increase, has a 10.8% importance degree for the battery failures in the marine hybrid propulsion systems.

#### 4. Conclusion

The paper aims to measure the impact of risk factors in the hybrid propulsion system. In this context, FAHP was applied in the risk assessment of diesel engine, generator, and battery failures in the hybrid propulsion system.

Considering the highest risks for three main criteria in diesel engine failures, generator failures, and battery failures with FAHP;

- $f_{11}$  which is the fuel oil leakage, has 34.3% for diesel engine failure,
- $f_{22}$  which is the cooling water pump failure, has 25.8% for generator failure
- $f_{34}$  which is the overheating and fire in the battery, has 32.5% for battery failure

It can be indicated that there are three alternatives for improvement for this safety assessment: the mechanical system, the electrical system, and the software system.

Considering the results of the FAHP, improving the mechanical system depicts the most important alternative compared with other systems because even though fuel oil leakage, cooling water pump failure, and overheating, and fire in the battery are not connected only mechanical system, also affect the mechanical system most. Risks can be prevented by using these improvements, and loss of life and property can be controlled.

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