



Assessing Functional Variability and Risk in Tugboat Design Using an Integrated FRAM-Fuzzy FMEA Framework

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Abstract

Tugboats are essential auxiliary vessels that play a vital role in port and offshore operations. The life cycle of tugboat involve complex couplings among hydrodynamic performance, propulsion systems, stability requirements, operational demands, production activities, regulatory compliance, and organizational coordination. Such socio-technical systems, variabilities may propagate significant technical and operational consequences. In this study, the functional resonance analysis method was applied to identify functional couplings, performance variability, and potential variability propagation throughout the tugboat design and construction lifecycle. The identified variability sources were subsequently transformed into failure modes and assessed using fuzzy failure mode and effects analysis. Expert judgments obtained from tugboat designers, shipyard managers, captains, and operators were represented through fuzzy numbers to address uncertainty in risk evaluation. fuzzy risk priority numbers were calculated based on occurrence, severity, and detection criteria. The results revealed that hull propulsion-incompatibility, propulsion system alignment deficiencies, accumulated functional resonance at ship delivery, verification shortcomings, classification compliance deficiencies, engineering team limitations, and coordination failures constitute the most critical risk areas. The findings demonstrate that risks emerge not only from isolated technical failures but also from interacting functional variabilities. The proposed framework supports proactive risk identification, prioritization, and more reliable tugboat design and construction processes.

Keywords: FRAM, fuzzy FMEA, tugboat design, functional variability, risk

1. Introduction

Ship design is a long and controlled process in which numerous technical and operational parameters are considered. Depending on different ship types, the main parameters are determined during the concept design stage, and ships are constructed through preliminary and detailed design processes [1]. In this process, identifying design-related problems before the construction stage is critical in order to prevent cost increases and schedule deviations. In this context, tugboats are special purpose marine vessels that perform various port operations, strait and canal transits, as well as rescue and assistance activities, and require high

performance [2]. Compared to other ship types, tugboats stand out with their more robust hull structures, powerful main engines, and propulsion systems with advanced maneuverability capabilities; therefore, they must be designed to satisfy structural strength, appropriate service speed, sufficient bollard pull capacity, dynamic stability, and operational safety criteria [3]. Reflecting their growing operational importance, the global tugboat market was valued at approximately USD 700.2 million in 2025 and is projected to reach USD 1,114.2 million by 2034, representing an increase of approximately 60% over the 2025-2034 period [4].

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Tugboat design and construction are realized as the result of a process involving complex and layered activities [5]. Therefore, the manner in which activities are generally performed throughout this process [Work-As-Done (WAD)] was defined using the Functional Resonance Analysis Method (FRAM) method, which is a Resilience Engineering (RE) approach [6]. Furthermore, in some studies, FRAM has been positioned within the Safety-II risk perspective [7]. Recently, in maritime safety studies, particularly with the RE approach, the ability of systems to adapt to changing conditions has become increasingly prominent. Rather than completely eliminating errors, this approach focuses on the system's abilities to anticipate, monitor, respond, and learn [8]. Although its importance has increased significantly in recent years, the systematic integration of the resilience approach into the tugboat design process remains limited. Existing studies in the literature mostly address accidents and root causes or operational safety separately [9], while holistic approaches evaluating technical design parameters together with system behavior have not been sufficiently developed. FRAM has a wide range of applications in the analysis of complex socio-technical systems and is used in many sectors such as aviation, healthcare, industrial operations, maritime transportation, railways, construction, oil and natural gas, information technologies, and nuclear systems [10]. In this approach, unlike traditional methods, risk analysis is addressed through the interactions and performance variability of functions in the daily operation of the system rather than through accidents and root causes [11]. The concept of functional resonance, which forms the basis of FRAM, states that variabilities among system components may combine and lead to unexpected outcomes [12]. Maritime applications of the FRAM have expanded significantly in recent years, particularly in the analysis of complex socio-technical systems involving operational variability, human interaction, and safety management. Existing studies can generally be categorized into four major thematic areas: maritime accident analysis, vessel traffic and operational management, emergency and hazardous cargo operations, and ship design and engineering applications. One major application area of FRAM is maritime accident analysis and systemic risk evaluation. Praetorius et al. [13] analyzed systemic failures through the Herald of Free Enterprise disaster, while Kee [14] compared different systemic accident-analysis techniques based on the Sewol ferry accident. Similarly, Wang et al. [15] evaluated the Eastern Star accident by comparing FRAM with other accident-analysis approaches. Studies conducted by Rammos [16] and Salihoglu and Beşikçi [17] and Ümitli et al. [18] further demonstrated the effectiveness of FRAM in identifying root causes and functional couplings in maritime

accidents. Another important research area involves vessel traffic management and operational resilience. Praetorius [19] and Praetorius et al. [20] investigated Vessel Traffic Service operations using FRAM to understand variability propagation in daily maritime operations. In addition, Kulkarni et al. [21] examined waterway traffic management and maritime resilience within the Baltic Sea region. Adhita et al. [22] analyzed ship operations from a Safety-II perspective, emphasizing adaptive operational performance under variable conditions.

FRAM has also been widely applied in emergency-response processes, hazardous cargo transportation, and autonomous maritime systems. Aguilera et al. [23] evaluated oil-spill emergency-response operations, while Qiao et al. [24] investigated emergency management for hazardous cargo leakage scenarios by integrating FRAM with Bayesian approaches. Ma et al. [25] focused on hazardous chemical transportation systems, whereas Nasur et al. [26] analyzed emergency unmooring procedures for autonomous and manned ships. Furthermore, Liu et al. [27] examined resilience in Arctic ship operations, while Zhao et al. [28] evaluated post-pandemic maritime transportation resilience. Human-machine interaction and autonomous ship safety were also investigated by Zhang et al. [29]. In addition to operational applications, several studies demonstrated the applicability of FRAM in ship engineering and design-related processes. Abaei et al. [30] developed a human-error prediction approach for ship operation in harsh environments, while Smith et al. [31] modeled operational risks associated with the Exxon Valdez accident. Smith et al. [32] further demonstrated the applicability of FRAM within ship-design processes.

Fuzzy Failure Mode and Effects Analysis (Fuzzy FMEA) complements FRAM by enabling variability-induced failure modes to be prioritized under conditions of uncertainty. Compared with classical FMEA, fuzzy-based approaches provide more realistic evaluations in systems involving ambiguity and expert uncertainty [33]. In maritime applications, Fuzzy FMEA has been employed in various operational and engineering problems. Zaman et al. analyzed ship-collision risks in the Malacca Strait using AIS-based data [34], while Akyüz et al. [35] applied Fuzzy FMEA to ship inspection processes. Akyüz and Çelik [36] investigated tanker accident scenarios using interval type-2 fuzzy FMEA. Sharma et al. [37] compared conventional and fuzzy-based FMEA approaches for reliability and maintenance assessment. Fuzzy FMEA has been utilized in oil spill analysis [38], ship-originated air pollution risk assessment [39], bunkering operations [40], and petrochemical transportation systems [41]. Design-oriented applications were also reported in shipyard occupational accidents [42], offshore engineering

systems [43], yacht-system design processes [44] and ship hydraulic steering systems [45]. These studies indicate that Fuzzy FMEA is not only applicable to operational safety assessment, but also highly suitable for early-stage ship design and engineering evaluations. Tugboat construction is shaped by couplings among design decisions, production processes, shipyard capabilities, equipment installation, classification requirements, and human factors, resulting in multi-layered cause-and-effect relationships [46]. These couplings may cause functional variabilities to combine and produce unexpected performance outcomes. Therefore, tugboat design should be addressed not only through performance indicators but also through a system behavior and variability-based approach [47].

In complex and multilayered systems such as shipbuilding, where technical criteria and engineering practices are predominant, how decisions are shaped within organizational and operational processes and what risks they involve remain issues requiring clarification. Previous tugboat studies have generally focused on individual topics, such as tugboat design [5,48], towing performance [3], escort capability, maneuverability, and harbor or offshore operations [2]. However, these studies do not provide an integrated framework for evaluating the lengthy and multistage design and construction process together with operational feedback. Addressing this gap by considering the process as a whole rather than examining its stages separately constitutes the main motivation of this study. Accordingly, FRAM was selected to model tugboat design and construction decisions as coupled functions and to examine how performance variability propagates through their couplings [32]. Fuzzy FMEA risk analysis was preferred to quantify the performance variabilities of decisions related to design, construction, and operational functions. The novelty of the proposed approach lies in integrating FRAM-based functional coupling and variability propagation analysis with Fuzzy FMEA-based risk prioritization and operational feedback within a single system-level framework.

The main objectives and contributions of this study can be summarized as follows:

- (i) An integrated FRAM-Fuzzy FMEA framework is proposed to represent the tugboat design and construction process, including operational feedback, as a network of coupled technical, production, regulatory, and organizational functions.
- (ii) A systematic approach is developed to transform FRAM-derived functional variabilities and propagation pathways into failure modes and to quantify and prioritize their risks through fuzzy aggregation of expert severity, occurrence, and detection assessments.
- (iii) The framework model is demonstrated through an actual 70-ton bollard-pull Azimuth Stern Drive (ASD) tug case

involving 16 main functions, seven support functions, and 40 functional variabilities. The high-priority failure modes corresponded with major warranty-period deficiencies, supporting the practical applicability of the framework and enabling the development of targeted risk-control measures.

2. Methodology

This study combines FRAM and fuzzy FMEA to analyse functional variability and risk in tugboat design and construction. The framework was applied to an ASD tugboat project with the input of five experts from tugboat design, construction, and operation. The method consists of two phases, as shown in Figure 1. In Phase 1, 16 main and seven support functions were modelled as Work-As-Imagined (WAI). Project and operational records were then examined as WAD to identify 40 functional variabilities and their propagation paths. In Phase 2, these variabilities were converted into failure modes and evaluated using Fuzzy FMEA. The calculated fuzzy risk priority numbers (FRPNs) values were ranked and compared with warranty records.

2.1. System Boundary and Process Definition

The system boundary was defined to include the activities that directly influenced the design, construction, testing, and delivery of the case tugboat. It includes concept, preliminary and detail design, performance and stability analyses, physical construction, outfitting, class approval, and acceptance tests. Operational experience and warranty records were incorporated as feedback sources for identifying WAD rather than being modelled as a separate operational stage. Only activities within this boundary were considered when defining

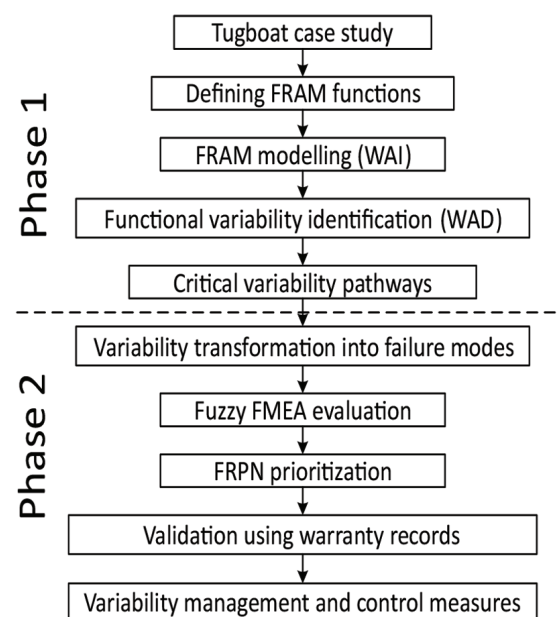


Figure 1. Analysis flowchart.

the FRAM functions and selecting the functional variabilities. The main stages are presented in Table 1.

Based on the system boundary and process stages defined above, the 40 functional variabilities were identified and selected through the following six-step procedure:

- Establishment of WAI: Technical specifications, approved design documents, classification requirements, contract documents, and testing and acceptance criteria were used.
- Identification of WAD: Field observations, construction and acceptance records, non-conformity reports, failure and warranty records, and expert interviews were examined.
- Identification of candidate variabilities: Differences between WAI and WAD were assigned to the relevant FRAM functions and couplings.
- Application of selection criteria: Variabilities were retained if they were within the system boundary, associated with a specific FRAM function, supported by project records or expert assessments, and capable of affecting downstream functions.
- Elimination and consolidation: Duplicate or overlapping items were merged, while items outside the system boundary or without a direct functional relationship were excluded.
- Expert review: The five experts reviewed the list in terms of relevance, clarity, and correspondence with the identified functions, resulting in a final list of 40 functional variabilities.

Table 1. Tugboat shipbuilding process stages.

Main phase	Sub-process/activity	Description
Design process	Concept design	Establishment of operational requirements and general design
	Preliminary design	Main dimensions and initial performance analysis
	Detail design	Engineering calculations and production drawings
Stability	Initial and final stability	Weight distribution control/trim and heel control
Hydrodynamic and performance analysis	Resistance analysis	Determination of hull resistance characteristics
	Powering analysis	Calculation of required engine power
	Propulsion system design	Determination of propulsion configuration
	Stability analysis	Evaluation of vessel stability criteria
Physical construction	Hull structure	Shell thicknesses, strength calculations, and construction
	Coating/paint system	Determination of corrosion protection systems
	Insulation	Fire, vibration, thermal, and acoustic insulation
Outfitting	Piping systems	Design of fuel, cooling, fire, etc. lines
	Electrical systems	Power distribution, lighting, and control systems
	Heating-ventilation and air conditioning (HVAC) systems	Heating, ventilation, and air conditioning
	Main engine/propulsion system	Integration of main engine, shaft, and propulsion equipment
	Auxiliary systems	Generators and auxiliary equipment
	Deck machinery	Cranes, windlasses, towing winches, etc. equipment
	Fire fighting systems	Fi-Fi systems
	Deck outfitting	Outfitting works
	Safety equipment	Life-saving and safety equipment
Navigation and communication	Navigation systems	Radar, ECDIS, AIS, etc. systems
	Communication systems	GMDSS and other communication systems
Testing and verification processes	Class approval	Compliance of design and production with class rules
	Factory acceptance test (FAT)	Testing of equipment at manufacturer facilities
	Harbour acceptance test (HAT)	System tests in harbour conditions
	Sea acceptance test (SAT)	Performance and system tests under sea conditions

2.2. FRAM Method

FRAM is an innovative approach developed by Erik Hollnagel and particularly used in the analysis of complex socio-technical systems. While traditional safety and risk analysis methods mostly focus on investigating the root causes of accidents, the FRAM approach aims to understand how a system actually works. This approach evaluates system performance not only through failures, but also through the continuously repeated “successful” functioning in daily operations [49].

Classical approaches assume that work processes are carried out in accordance with procedures, rules, and standards, and they consider deviations as exceptional situations. However, in real working environments, operations do not always proceed as planned, and continuous adaptations are made through the interaction of humans, organizations, and technology. Therefore, the starting point of system analysis is not how the work should theoretically be performed (WAI), but rather how it is actually performed in practice (WAD). The main reason why operations are mostly carried out successfully in daily activities is the ability of system components to adapt to variable conditions. This adaptation process occurs through small-scale adjustments and flexible decision-making mechanisms. The FRAM approach considers adaptive behaviors as an integral part of system performance and aims to analyze how performance variability emerges rather than focusing solely on errors. In this context, FRAM is not a classical risk or accident analysis method, but rather a qualitative modeling approach that explains system behavior [6].

2.2.1. FRAM functions

The FRAM method is based on modeling the functions within a system and the couplings among these functions in order to understand how the system operates. In the analysis process, the functions existing within the system are first identified, and the connections among these functions are revealed. Subsequently, the typical performance variabilities of these functions are evaluated, and the functional resonance that may occur within the system are analyzed. According to the FRAM approach, a function is a set of activities performed to achieve a specific objective. These functions may be simple or complex and play a fundamental role in the formation of system outputs. The correct identification of functions is critically important for the accuracy of the analysis. Each function is defined in the FRAM methodology through six basic aspects: Input, Output, Precondition, Resource, Control, and Time. Input: Information, instruction, or warning that initiates the function and is used to produce an output. Output: The result of the function, which may become an input for another function. Precondition: Conditions that

must be satisfied before the function begins. Resource: Information, equipment, and workforce required during the execution of the function. Control: Rules, procedures, and supervision mechanisms that ensure the function produces the intended result. Time: The time factor that constrains or directs the execution of the function [6]. The aspects of the FRAM function cell are shown below in Figure 2.

2.2.2. Performance and variability

In the FRAM model, functions are in continuous couplings with each other. These constitute the main source of variability in system performance. The couplings established among functions through input-output relationships, control mechanisms, and resource utilization play an important role in understanding system behavior. The relationships among functions are not always dependent on a linear time sequence. In some cases, functions may occur in parallel or indirectly affect each other. Therefore, system analysis should include not only sequential processes but also simultaneous couplings.

In the FRAM approach, performance variability is accepted as a natural characteristic of the system. Human, organizational, and technological components generate variability at different levels. While the human factor generally exhibits high frequency variability, technological systems display a more stable structure. Criteria called Common Performance Conditions are used for the evaluation of performance. These criteria include factors such as resource adequacy, communication quality, working environment, time pressure, and organizational support. Processes such as tugboat design, which involve human-technology-organization structures, contain high levels of variability. Therefore, variability levels may be classified using linguistic expressions in performance evaluations. This approach enables the dependencies among system functions to be understood more clearly [50].

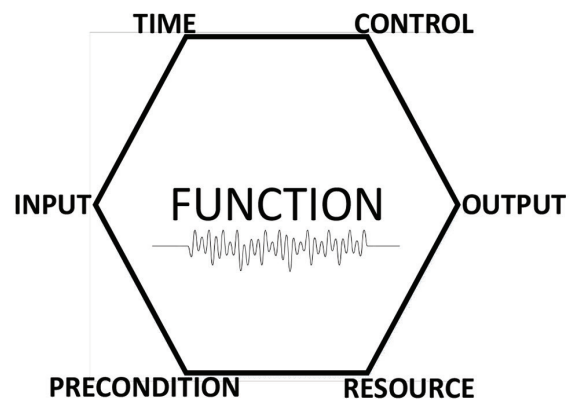


Figure 2. FRAM Function cell and its aspects.

2.2.3. Variability management and control measures

In the FRAM methodology, the analysis of variability is a critical stage for understanding system performance. Small variabilities occurring during daily operations may not individually cause system failure. However, when these variabilities couple with other functions, a functional resonance may emerge and lead to serious consequences. FRAM provides an important framework for managing variability in system performance. In this context, systems are required to develop resilience and adaptation capability. The ability of systems to respond rapidly and effectively to changing conditions is a determining factor in controlling risks [51]. During the variability management process, continuous monitoring, feedback, and learning mechanisms should be established. In this way, system performance can be continuously evaluated and opportunities for improvement can be identified [52].

One of the most important contributions of the FRAM method is that it enables complex systems to be analyzed in a holistic manner. Evaluating system performance not only through failures but also through normal operations is one of the strong aspects of the method [6]. However, the fact that the method is a qualitative analysis approach brings certain limitations. Since the analysis results largely depend on expert opinions, subjective evaluations may occur. In addition, the difficulty of data collection processes and the long duration of analysis are among the disadvantages of the method [24]. In order to overcome these limitations, the FRAM method is integrated with multi-criteria decision-making techniques, fuzzy logic, and quantitative risk analysis methods. In this way, qualitative analysis results can be transformed into numerical values, enabling more concrete risk evaluations [53]. The output variability belonging to functions may be formulated as follows. Depending on the scale of the model, clearly determining these requires highly complex and lengthy calculations [54-56].

$$\Delta v_{O,F1} = \sum_{F1} \left((\Delta v_{I,1} * w_{I,1}) + (\Delta v_{R,1} * w_{R,1}) + (\Delta v_{C,1} * w_{C,1}) + (\Delta v_{PC,1} * w_{PC,1}) \right) \quad (1)$$

In the example of the interacting F1 and F2 functions, the variability relationship can be expressed mathematically as follows:

$$\Delta v_{O,F_2} = \left[\left((\Delta v_{i,2} * w_{i,2}) + (\Delta v_{r,2} * w_{r,2}) + (\Delta v_{c,2} * w_{c,2}) + (\Delta v_{pc,2} * w_{pc,2}) \right) + \Delta v_{O,F_1} \right] \quad (2)$$

2.3. FMEA Method

The risks that may arise from functional variabilities were evaluated by integrating the fuzzy FMEA method, and *FRPN* were calculated for each failure mode. Accordingly, the performance variabilities identified through the FRAM analysis were transformed into semi-quantitative risk scores, and critical risk areas within the design process were identified. FMEA is a risk analysis method that systematically evaluates potential failure modes that may occur in products, processes, or systems and the effects of these failures [57].

In multidisciplinary engineering processes such as tugboat design, it is used as an important tool especially in the analysis of systems, design, construction, quality, reliability, and their couplings [58]. The tugboat design process has a complex structure requiring the combined evaluation of hull structure, hydrodynamic performance, main engine and propulsion system integration, stability, structural integrity, bollard pull performance, and operational requirements. Therefore, the early identification of errors that may arise during the design stage is critically important. FMEA provides an effective approach for identifying potential failure modes in this process, analyzing the effects of these failures on design and operation, and prioritizing risks. The method was first developed in military applications in the 1940s and was later systematized by NASA and became widely used in engineering applications [59].

For each failure mode, RPN values were calculated through severity, occurrence probability, and detectability scales, and the risks were therefore classified according to their priority levels. This approach enabled the identification of necessary improvement and control mechanisms within the design process [60]. FMEA was considered a proactive method that provided the opportunity to predict potential future problems by utilizing past design experiences and to reduce these risks during the early stages of design [61]. In this respect, the method was found to be compatible with the FRAM approach, as it enabled the semi-quantitative evaluation of the performance variabilities identified through FRAM and supported the establishment of a holistic risk assessment framework.

2.3.1. FMEA analysis procedure

The three fundamental evaluation criteria most commonly used in FMEA applications are Occurrence (O), Severity (S), and Detection (D) parameters. Failure modes identified within the tugboat design process are evaluated and scored according to these three factors based on expert opinions. According to the United States Department of Defense (1949), a failure mode is defined as the inability of a function within the tugboat design system to provide the expected performance, operate insufficiently or irregularly, or produce

undesired results [62]. Effect refers to the consequences of these failures on system performance, operational safety, and the end user. The Severity (S) parameter is determined according to the worst potential consequence of the relevant failure mode and is particularly evaluated in terms of safety of life, equipment damage, and operational losses.

2.3.2. Fuzzy FMEA

Fuzzy logic enables direct operation with linguistic expressions used in FMEA and models the uncertainty in expert evaluations more realistically. This approach allows uncertain or qualitative information to be effectively used in risk prioritization. In this context, a fuzzy logic-based structure was established by considering the O, S, and D parameters through linguistic variables in the evaluation of failure risk. In FMEA, the prioritization of failure modes is often considered as a multi criteria decision-making process, and in the literature, the integration of fuzzy logic with

methods such as TOPSIS, VIKOR, AHP, and DEMATEL is widely used [58,61]. The classical FMEA approach includes certain limitations such as the assumption that risk factors have equal weights, different O, S, D combinations being able to produce the same RPN value, and evaluations being limited to precise numerical expressions. Therefore, it is necessary to perform a more flexible and representative evaluation using fuzzy linguistic variables and membership functions. In this study, potential failure modes, effects, and causes related to the functions determined by FRAM were analyzed using fuzzy FMEA. Evaluations were performed by experts according to the O, S, and D scales specified in Tables 2, 3, 4. These assessments were processed through fuzzification, and *FRPN* were subsequently calculated through the defuzzification procedure. Based on the obtained *FRPN* values, risk prioritization was performed, and corrective control measures for critical functions were identified [63,64].

Table 2. Fuzzy ratings for occurrence of a failure [57,65].

Probability	Probability of occurrence	Failure probability	Fuzzy number
Almost None: Has not occurred before	Remote (R)	$\leq 1/1.500.000$	(1,1,2)
Remote Probability: Occurred very very rarely	Low (L)	$1/150.000$	(2,3,4)
Very Low: Relatively infrequent failures		$1/15.000$	
Low: Failures occasionally occurring		$1/2000$	(4,5,6)
Minor: Occurring in small numbers	Moderate (M)	$1/400$	
Medium: Occurring at medium frequency		$1/80$	
Slightly High: Occurring in slightly high numbers	High (H)	$1/20$	(6,7,8)
High: Occurring in high numbers		$1/8$	
Very High: Occurring in very high numbers	Very High (VH)	$1/3$	(8,9,10)
Almost Certain: Failure is almost certain		$> 1/2$	

Table 3. Fuzzy ratings for severity of a failure [57,65].

Severity of effect	Effect	Fuzzy number
No effect	None (N)	(1,1,2)
Failure causing confusion in tugboat design	Very minor (VM)	(1,2,3)
Failure slowing down tugboat design	Minor (MIN)	(2,3,4)
Failure causing short-term disruption in tugboat design	Very low (VL)	(3,4,5)
Failure causing short-term disruption in tugboat design, production, and organization	Low (L)	(4,5,6)
Failure causing moderate losses in tugboat design, production, and decision-making processes	Moderate (MOD)	(5,6,7)
Failure having an effect causing complete system damage, incomplete production, and delay	High (H)	(6,7,8)
Failure having a destructive effect causing complete damage to tugboat design, production losses, etc.	Very high (VH)	(7,8,9)
Potential failure causing severe damage in tugboat design, production stoppage, and multiple fatalities	Hazardous with warning (HAZ)	(8,9,10)
Potential failure having an effect that may lead to catastrophe on the tugboat, organization, and environment	Hazardous without warning (CAT)	(9,10,10)

Table 4. Fuzzy ratings for detection of a failure [57,65].

Likelihood detection	Detection	Fuzzy number
Detectability of the cause of the potential failure and the subsequent failure is almost certain	Almost certain (AC)	(1,1,2)
Detectability of the cause of the potential failure and the subsequent failure is very high	Very high (VH)	(1,2,3)
Detectability of the cause of the potential failure and the subsequent failure is high	High (H)	(2,3,4)
Detectability of the cause of the potential failure and the subsequent failure is moderately high	Moderately high (MH)	(3,4,5)
Detectability of the cause of the potential failure and the subsequent failure is moderate	Moderate (M)	(4,5,6)
Detectability of the cause of the potential failure and the subsequent failure is low	Low (L)	(5,6,7)
Detectability of the cause of the potential failure and the subsequent failure is very low	Very low (VL)	(6,7,8)
Detectability of the cause of the potential failure and the subsequent failure is remote	Remote (R)	(7,8,9)
Detectability of the cause of the potential failure and the subsequent failure is unlikely	Very remote (VR)	(8,9,10)
Detectability of the cause of the potential failure and the subsequent failure is impossible	Impossible (IMP)	(9,10,10)

2.3.2.1. Fuzzy representation of expert evaluations

In fuzzy sets, different membership functions such as triangular, trapezoidal, and bell shaped curves are used in order to determine the membership degrees of elements. Among these functions, triangular and trapezoidal fuzzy numbers are particularly prominent as the most commonly preferred approaches in applications. Membership functions play an important role in modeling situations involving uncertainty and enable the representation of complexities encountered in fuzzy logic systems. Determining membership degrees through linguistic expressions allows the boundaries of system parameters to be defined [65,66]. A fuzzy set is generally expressed as:

$$A = \{(x, \mu_A(x)) : x \in X, \mu_A(x) \in [0,1]\} \quad (3)$$

Here, X represents the universal set, A represents the fuzzy set, μ_A denotes the membership function of the fuzzy set, and $\mu_A(x)$ represents the membership degree of the element x belonging to the related set. The membership degree varies between 0 and 1, where the value 0 indicates that the element does not belong to the set, while the value 1 represents full membership. Intermediate values indicate partial membership. The triangular membership function used in this study is defined by three parameters, namely the lower limit a , the peak point m , and the upper limit b , and satisfies the condition $a \leq m \leq b$. The triangular membership function is shown in Figure 3.

Triangular membership functions are also effectively used in the quantification of linguistic variables. The triangular membership function used in this study is defined by three parameters, namely the lower limit a , the peak point m , and the upper limit b , and satisfies the condition $a \leq m \leq b$. The fuzzy membership structure used in this study was established based on the approaches proposed by Liu et al.

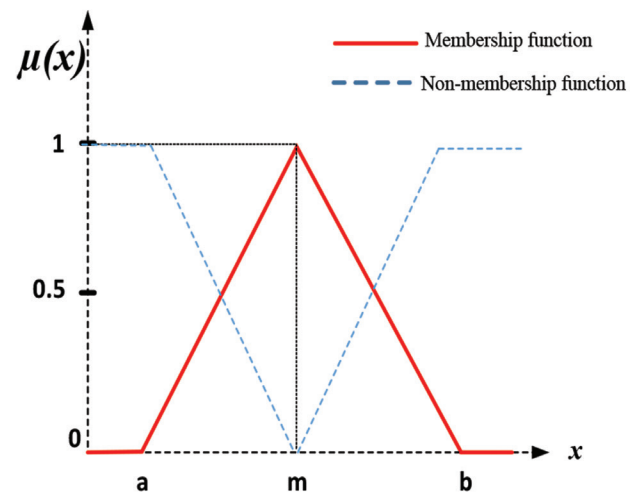


Figure 3. Triangular membership function.

[57] and Wang et al. [65]. The mathematical representation of the membership function is given below:

$$\mu_{A(x)} = \begin{cases} 0, & x \leq a \\ \frac{x-a}{m-a}, & a < x \leq m \\ \frac{b-x}{b-m}, & m < x \leq b \\ 0, & x > b \end{cases} \quad (4)$$

2.3.2.2. Aggregation of expert opinions

In the study, risks associated with tugboat design and construction were evaluated using a Fuzzy FMEA approach integrated with FRAM-based variability analysis. Linguistic expert evaluations were transformed into triangular fuzzy numbers according to the scales given in Tables 2, 3, and 4. For each failure mode, the fuzzy evaluations provided by the experts were aggregated using the arithmetic mean

method. The aggregated occurrence probability value is expressed as:

$$\tilde{O} = \frac{1}{n} \left(\sum_{i=1}^n a_i, \sum_{i=1}^n m_i, \sum_{i=1}^n b_i \right) \quad (5)$$

2.3.2.3. Calculation of the FRPN

The *FRPN* is a measure that numerically expresses the risk level of each potential failure mode. As shown in equation 6, the *FRPN* value is calculated by multiplying the occurrence probability (O), severity (S), and detection (D) values.

$$\widetilde{FRPN} = \tilde{O} \otimes \tilde{S} \otimes \tilde{D} \quad (6)$$

The multiplication of triangular fuzzy numbers was performed on a component basis and is expressed as:

$$\widetilde{FRPN} = (a_o a_s a_d, m_o m_s m_d, b_o b_s b_d) \quad (7)$$

Through this approach, the risk levels related to failure modes were represented not only by a single precise value but also by a fuzzy interval including uncertainty.

2.3.2.4. Defuzzification

In order to rank the fuzzy *FRPN* values and perform comparative risk evaluation, a defuzzification process was applied. In this study, the centroid method was preferred as the defuzzification method. The defuzzified *FRPN* value is calculated as:

$$FRPN_{crisp} = \frac{\sum_{i=1}^n x_i \mu(x_i)}{\sum_{i=1}^n \mu(x_i)} \quad (8)$$

As a result of this process, fuzzy risk values were transformed into a single numerical value, and it became possible to determine the risk priorities of failure modes. Thus, the failure modes creating critical risks were quantitatively ranked and prioritized.

2.4. Case Study and Expert Selection

In this study, a FRAM-based framework was developed through a real tugboat building project. Initially, the functional couplings of tugboat design and building processes under ideal operational conditions were established. Then, the interactions among variable functions were analyzed through a real tugboat building case. The investigated tugboat case was built based on a local design approach rather than a ready-made design package, in a shipyard possessing limited infrastructural resources and located far from major logistics supply chains. Furthermore, the shipbuilding company maintained a highly limited control and engineering team throughout the project lifecycle. The

construction process exceeded the original project schedule and the tugboat was delivered with delay. The most dominant source of operational problems was identified as excessive shaft angles between the main engine output and ASD input shafts, resulting in bearing-related problems and vibration. In order to reduce the angular difference along the propulsion line, two cardan shafts were integrated into the shaft system. Following the provisional acceptance of the tugboat, more than 400 user-reported deficiency notifications were recorded during the warranty period. Among these records, accommodation sweating caused by the Heating, Ventilation and Air Conditioning (HVAC) system, high vibration, alarm monitoring system deficiencies, improper material usage, and equipment failures were the most prominent issues. In addition, numerous deficiency reports were submitted regarding insufficient chain-locker dimensions, accommodation cabin arrangements, and deck equipment integration problems. The principal particulars and technical information of the tugboat used in this study are presented in Table 5.

Subsequently, the Fuzzy FMEA analysis stage was carried out based on the identified functional variabilities. Potential variabilities arising from functional couplings were defined as failure modes, and the associated risks were evaluated through a semi-quantitative risk assessment approach. FRAM analysis requires field observations and expert evaluations [67]. Similarly, expert evaluations ensure that the Fuzzy FMEA analysis produces accurate results [68]. In this context, general information regarding the experts consulted in the study is presented in Table 6. In order for the study to produce reliable and realistic results, the experts

Table 5. Tugboat main particulars.

Parameter	Ship particular
Vessel type	Open sea tugboat
Length overall (LOA)	32 m
Moulded Beam	11.83 m
Moulded Depth	5.55 m
Bollard pull (BP)	70 t
Propulsion type	Azimuth Stern Driver (ASD)
Service speed	13 kn
Gross tonnage	546
Net tonnage	164
Hull material	Steel
Main engine power	2 x 2100 kW
Classification notation	1A5 Y ESCORT TUG + M AUT-8h Fi-Fi1
Keel laying date	01 January 2018
Delivery date	30 May 2019

Table 6. General qualifications of the experts.

Expert code	Position	Experience (years)	Professional qualifications
E1	Tugboat design department director	20	Ph.D. Naval Architecture and Marine Engineering
E2	Tugboat designer	10	B.Sc. Naval Architecture and Marine Engineering
E3	Tugboat shipyard manager	15	M.Sc. Naval Architecture and Marine Engineering
E4	Tugboat captain	12	B.Sc. Maritime Transportation and Management Engineering, Master Mariner
E5	Tugboat operator/fleet owner	25	B.Sc. Maritime Transportation and Management Engineering, Master Mariner

were selected from individuals with design, construction, and operational experience. The main reason for this is that certain deficiencies that cannot be foreseen during the design stage may only emerge during the construction and operational processes. Similarly, experiences conveyed solely by designers and construction teams remain incomplete without the contribution of operator users who know how the tugboat behaves under actual operating conditions and what performance limitations it encounters. Therefore, the expert group was formed with the aim of bringing together knowledge and experience covering the entire lifecycle of the tugboat.

2.5. Sensitivity and Uncertainty Analysis

Fuzzy numbers address the vagueness of linguistic evaluations but do not directly quantify expert disagreement or the sensitivity of the results to model assumptions. Therefore, three supplementary analyses were conducted to evaluate the robustness of the *FRPN* results. First, agreement among the five experts was assessed separately for occurrence, severity, and detection using tie-corrected Kendall's *W* formula as given in Equation 9. Kendall's coefficient of concordance (*W*) is a non-parametric measure used to evaluate for rank correlation. The coefficient ranges from 0 to 1, where values close to 0 indicate weak agreement and values close to 1 indicate strong agreement [69].

$$W = \frac{12 \sum_{i=1}^n (R_i - R^-)}{m^2(n^3 - n) - m \sum_{j=1}^m T_j} \quad (9)$$

Second, a leave-one-expert-out (LOEO) analysis was performed by excluding each expert and recalculating the *FRPN* values and rankings. Finally, parameter sensitivity was tested using occurrence, severity, and detection dominant weighting scenarios of (0.50,0.25,0.25), (0.25,0.50,0.25), and (0.25,0.25,0.50) by the equation 10. Spearman's rank correlation and maximum rank shifts were used to compare the results with the baseline ranking.

$$FRPN_w = \frac{O_a^{3w_o} O_a^{3w_s} O_a^{3w_d} + O_m^{3w_o} O_m^{3w_s} O_m^{3w_d} + O_b^{3w_o} O_b^{3w_s} O_b^{3w_d}}{3} \quad (10)$$

3. Analysis

3.1. FRAM Analysis

3.1.1. Defining tugboat design functions as WAI

The tugboat design and construction process was modeled by considering the process from the definition of operational requirements to the delivery of the vessel. The related functions were developed by assuming that the construction process progressed in accordance with the planned project schedule (WAI). The system consisted of 16 main and 7 sub-functions as given in Table 7 covering preliminary design, performance analyses, propulsion system selection, stability verification, class compliance controls, production organization, and verification/revision processes. The first function initiating the system is Sub1, which defines the customer/shipowner demand, while the final function terminating the system is Sub7, which represents the delivery of the vessel. The functions between F1 and F8 are preparation functions, the functions between F9 and F13 are detail process functions, the functions between F14 and F16 are control functions, and the functions between Sub1 and Sub7 are support functions.

Tugboat design was modeled by accepting the existence of standard functions required to be performed. This assumption includes the basic functions and aspects that should exist within the broadest framework. While projects having similar design characteristics are received as standardized design packages, some intermediate forms are redesigned by being subjected to re-analysis processes. Tugboat design and construction have a complex process realized through HuMan (M), Technology (T), and Organization (O) couplings [44]. If all functions involved in all construction processes were defined in detail, the modeling framework would become excessively broad, which would cause deviations in the analysis results. By defining boundaries for the FRAM model through the functions, the analysis was prevented from becoming excessively complex and more consistent results were achieved.

The primary requirements are the intended service, main engine power, propulsion system, and bollard pull

Table 7. FRAM function description and complex group.

No	Type	Function	M-T-O
F1	Preliminary	To define operational requirement	M-O
F2	Preliminary	To define preliminary design parameters	M-T
F3	Preliminary	To perform performance analyses	M-T
F4	Preliminary	To determine main engine power	M-T
F5	Preliminary	To decide propulsion system	M-T-O
F6	Preliminary	To determine weight distribution	M-T
F7	Preliminary	To check initial stability	M-T
F8	Preliminary	To estimate bollard pull target	M-T
F9	Development	To arrange deck equipment	M-T-O
F10	Development	To determine accommodation and bridge layout	M-T-O
F11	Development	To design engine room arrangement	M-T-O
F12	Development	To define firefighting and safety systems	M-T-O
F13	Development	To start physical construction	M-T-O
F14	Control	To check building class-maritime rules	M-T-O
F15	Control	To organize shipbuilding	M-O
F16	Control	To verify and revise project	M-O
Sub1	Support	To give the main profile	M-O
Sub2	Support	To meet design constraints	M-T-O
Sub3	Support	To utilize available data sources	M-T
Sub4	Support	To define equipment list	M-T-O
Sub5	Support	To provide project team	M-O
Sub6	Support	To ensure shipyard infrastructure	T-O
Sub7	Support	To deliver the vessel	M-T-O

capacity. During the concept design stage, customer/shipowner requirements must be established within a consistent framework. Design according to the service purpose is essential. When this is not clearly determined, the operational framework expands and negatively affects equipment selection and the construction process. Strong main engine and propulsion performance are the principal capabilities of a tugboat. Harbor or offshore tugboats require specific characteristics regarding draft heights and propulsion systems according to their service area. In ports and terminals, lower-draft propulsion systems are preferred. In escort and towing services, voith-type propulsion systems are highly efficient in terms of maneuverability. In tugboats, reinforced skeg structures, bulwark lines, and bow and stern form constructions facilitate harsh operational working conditions. The installation process of the propulsion system region to the hull requires highly sensitive engineering solutions. Bridge control consoles are equipped to control and monitor both bow and stern operations [1,5,70]. The engine room arrangement should be designed in a way that facilitates equipment maintenance operations.

Tugboats are generally propelled and driven by two main engines and two propulsion systems. According to electrical load calculations, a minimum of two diesel generators are installed. In addition, auxiliary equipment such as main engine and diesel generator coolers, compressors, hydraulic power units, sewage treatment systems, oily water separators, oil and fuel separators, air conditioning units, hydrophore units, pumps, filters, batteries, rectifiers and inverters, transformers, exhaust silencers, and main and distribution switchboards are included in engine room equipment arrangements. For external firefighting, water and foam-type liquids are sprayed from fire monitors through high-suction pumps located in the engine room. Accommodation arrangements should be equipped according to the minimum safe manning certificate based on the service class of the tugboat. Master and chief engineer cabins are designed as separate cabins [1,5,70].

Although there are certain variations in the rules depending on tonnage and classification society, tugboat construction should be subjected to control and inspection through classification societies. Structural, outfitting, and piping

drawings, physical construction, and the quality standards of equipment and materials are subject to class approval. It is essential that physical construction progresses in coordination with the class approval process. Progress is achieved as a result of periodic class surveys. At this stage, drawing and field remarks issued by the class should be followed and subjected to a re-approval process. Similarly, the employment of design and project teams together with the adequacy of shipyard infrastructure are sub-functions having extensive interaction originating from human and organizational factors [45,71]. Each function was modeled using the six basic aspects of FRAM, namely input, output, precondition, resource, control, and time, as shown in the example in Table 8. Thus, dependencies among functions and the propagation of output variabilities throughout the system were analyzed.

The couplings among the identified functions were modeled using the FRAM Model Visualiser software and are presented in Figure 4. In the model, each function was defined by considering the aspects of input, output, precondition, resource, control, and time.

Figure 5 FRAM functional coupling graph shows that the connection intensity among system functions is not distributed homogeneously throughout the model. The FRAM functions have a total of 108 couplings. The function with the highest number of couplings is F13 (to start shipbuilding). The function with the lowest number of couplings is the Sub1 (to give main profile). In particular, F13, F3, and F9 were identified as the functions having the highest number of couplings. The functions F10, F11, F12, and F15, which exhibit moderate coupling intensity, are mainly associated with detail design, compartment

Table 8. F2-F3 function aspects.	
F2-to define preliminary design parameters	
Input	Concept design determined
	Contract-technical specification prepared
Output	Main dimensions (L, B, T, D) determined
	Hull form and displacement preliminary assumption determined
	Total ship resistance determined
	Propulsion and maneuvering characteristics determined
	Bollard pull preliminary assumption determined
	General arrangement plan draft prepared
Precondition	Basic performance and mission requirements determined
Resource	Design software, similar vessel database, hydrodynamic knowledge
Control	Design criteria, class limitations, draft and port constraints
Time	-
F3-to perform performance analysis	
Input	Main dimensions (L, B, T, D) determined
	Hull form and displacement preliminary assumption determined
	Total ship resistance determined
	Propulsion and maneuvering characteristics determined
	Bollard pull preliminary assumption determined
	General arrangement plan draft prepared
Output	Preliminary design finalized
	Model test results
	Start detail design
Precondition	Basic performance and mission requirements determined
	Design criteria, class limitations, draft and port constraints
Resource	Design software, similar vessel database, hydrodynamic knowledge
Control	-
Time	-

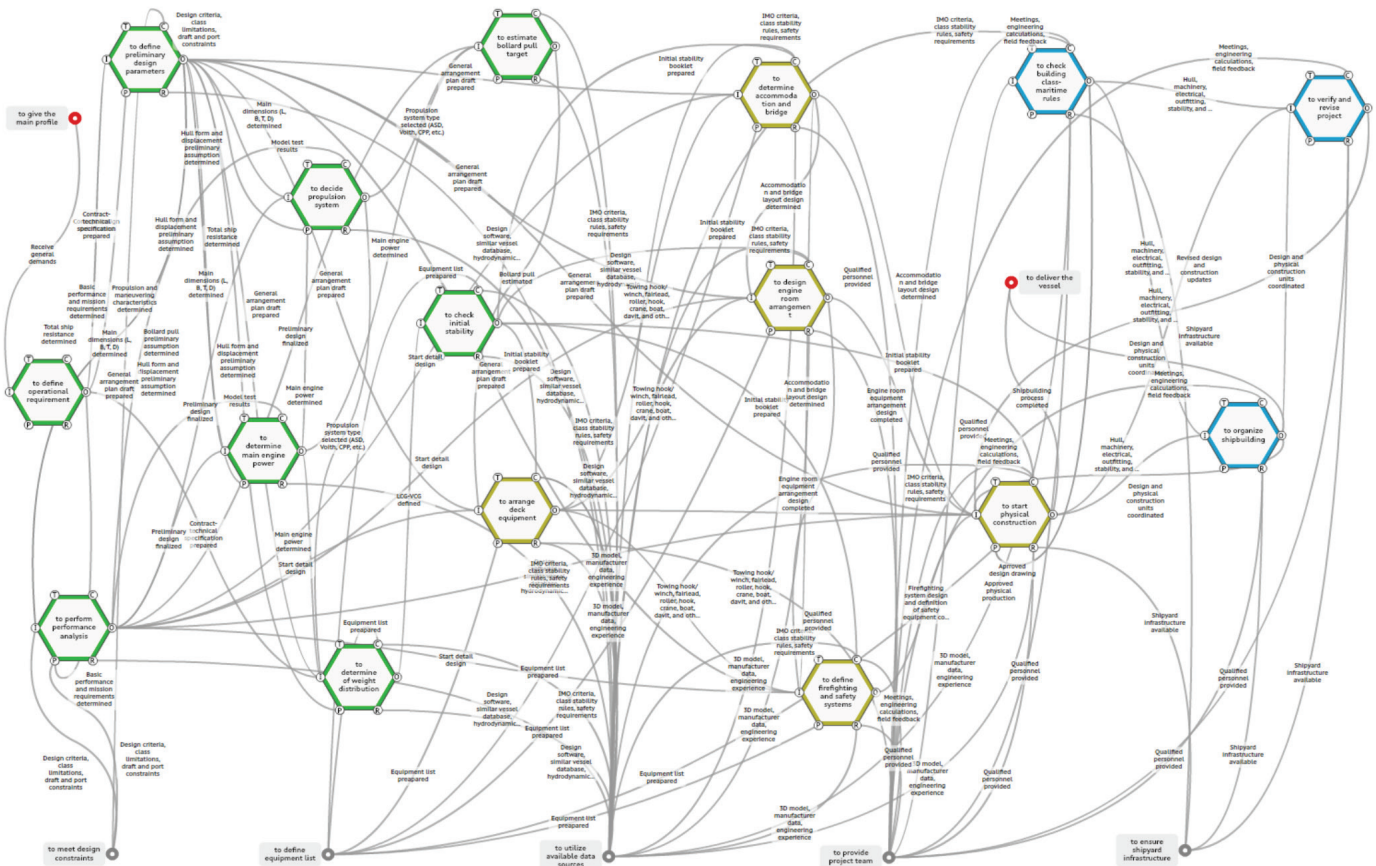


Figure 4. FRAM analysis visualization with functional couplings.

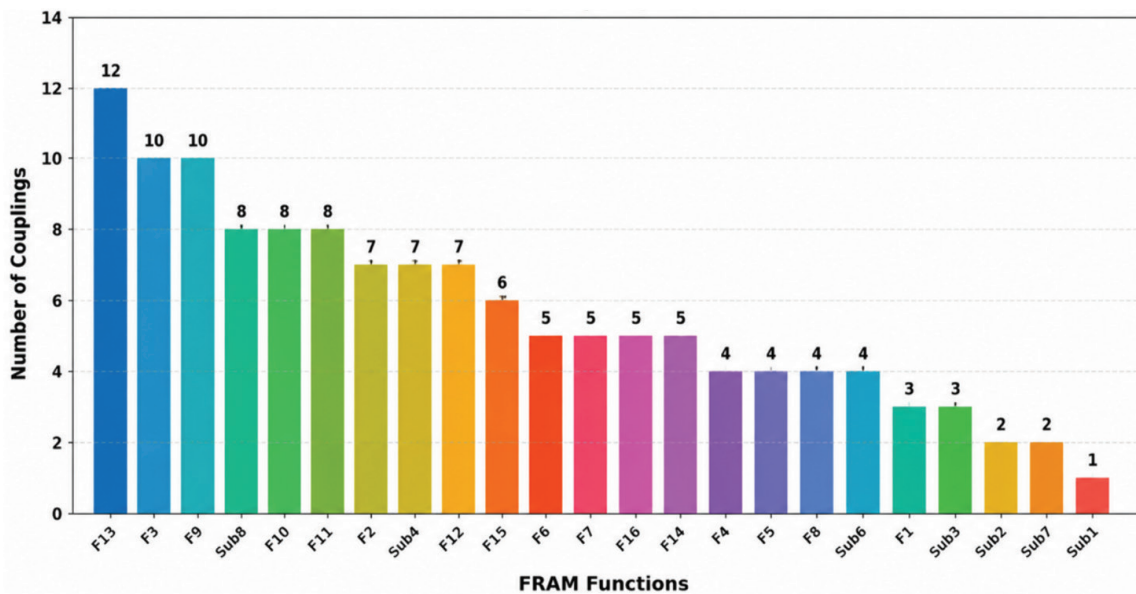


Figure 5. FRAM functional coupling intensity.

arrangements, and verification processes. Support functions with lower coupling levels were evaluated as auxiliary structures ensuring system continuity in terms of personnel, data flow, and infrastructure support, even though they do not directly generate critical resonance.

3.1.2. Aggregation of functions variability as WAD

In the tugboat case, the first major problem identified was the high shaft angle between the main engine output and ASD input caused by main engine arrangement related limitations. As shown in Figure 6, additional bearings and universal/cardan shafts were required due to the angular shaft arrangement between the main engine and the ASD unit. The approximately 19° angular difference was accommodated through the use of two cardan shafts and two additional bearings. Although the arrangement was considered acceptable by both the design team and the main engine-ASD manufacturers, the approximately 19° shaft angle is considerably higher than the 5.5° angle generally permitted in conventional straight-shaft installations. This increased angular difference may contribute to alignment deficiencies, bearing wear, and vibration-related problems. Due to these angular differences, bearing clearances decreased as a result of overheating problems occurring in the shaft bearings. Although the bearings are designed to withstand temperatures up to 225°C , overheating problems were observed during operation. Before the improvement works, vibration measurements on the ASD unit reached 77.6 mm/s in the horizontal direction, 162.9 mm/s in the transverse direction, and 203.4 mm/s in the vertical direction. Furthermore, due to vibration complaints originating from the shaft bearings, the vessel was taken out of service and corrective actions were attempted through re-bearing operations. Following shaft-bearing replacement

during the warranty period, vibration levels were reduced to acceptable ISO limits. The critical resonance pathway of the related problem in terms of FRAM functions is presented in Figure 7.

The functional resonance aggregation pathway of the propulsion-system problems was identified as F1-F2-F4-F5-F11-F13. The variabilities occurring within the main performance requirements, acceptance criteria, and calculation processes affected the outputs of the propulsion-system selection function as inputs. F5 directly affected F11, while F11 subsequently affected the F13. In addition, insufficient controls within the F16 created negative variability on the shaft arrangement in the engine room. Furthermore, insufficient qualified personnel, limited shipyard capabilities, misinterpretation of previous design data, and design constraints constituted sources of variability affecting the outputs of the related propulsion-system functions.

The accommodation spaces of the vessel are climatized by a seawater-fed chiller system located in the engine room. Fan-coil units belonging to the system are installed within the cabins. In the project, sweating caused by the HVAC system resulted in leakage into the wheelhouse and personnel cabins. Accommodation panel coverings and insulation materials became wet, and some sections became unusable. As a corrective action, additional drains were opened on the gutter bars and the insulation of the fan-coil pipes was revised. This situation negatively affected personnel living conditions on board. It was observed that the related problem negatively affected the system by generating variability.

The outputs of the F1-F2, concept design, preliminary design, and general arrangement plan, served as inputs for F10 and transferred variability into this function. The output of the F10 (to determination of the accommodation and

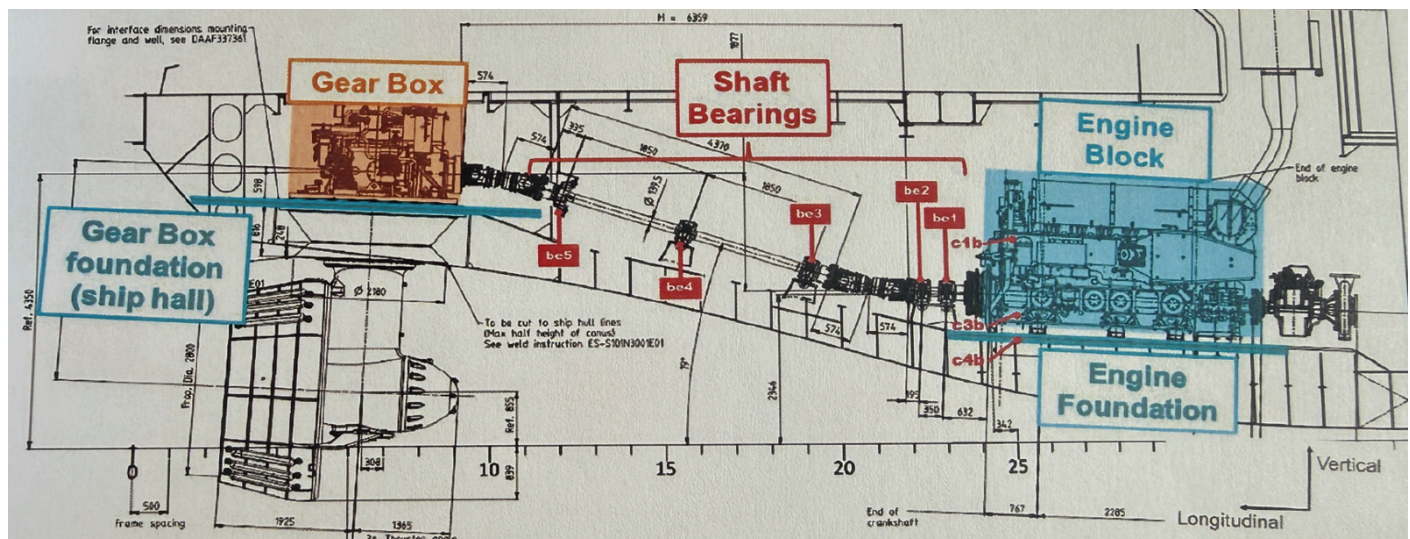


Figure 6. Main engine-ASD angular shaft alignment configuration.

bridge layout), affected the Sub7-vessel delivery function as an input of F13. Furthermore, insufficient personnel (Sub5), shipyard infrastructure deficiencies (Sub6), and equipment selection deficiencies and faults (Sub4) originating from

the other support functions contributed to the growth of variability. The F1-F2-F10-F13-Sub7 sequence represents the critical variability pathway of the related problem as given in Figure 8.

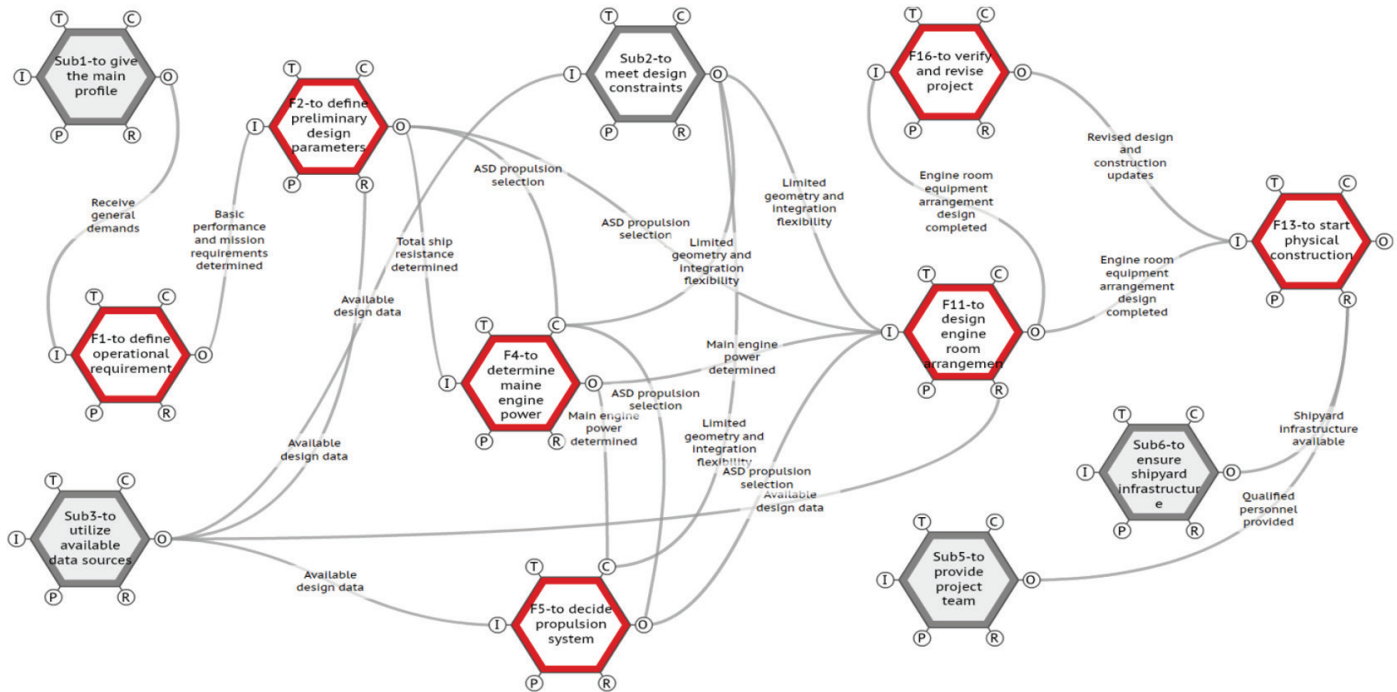


Figure 7. Functional resonance pathway associated with the main engine-ASD angular shaft alignment problem.

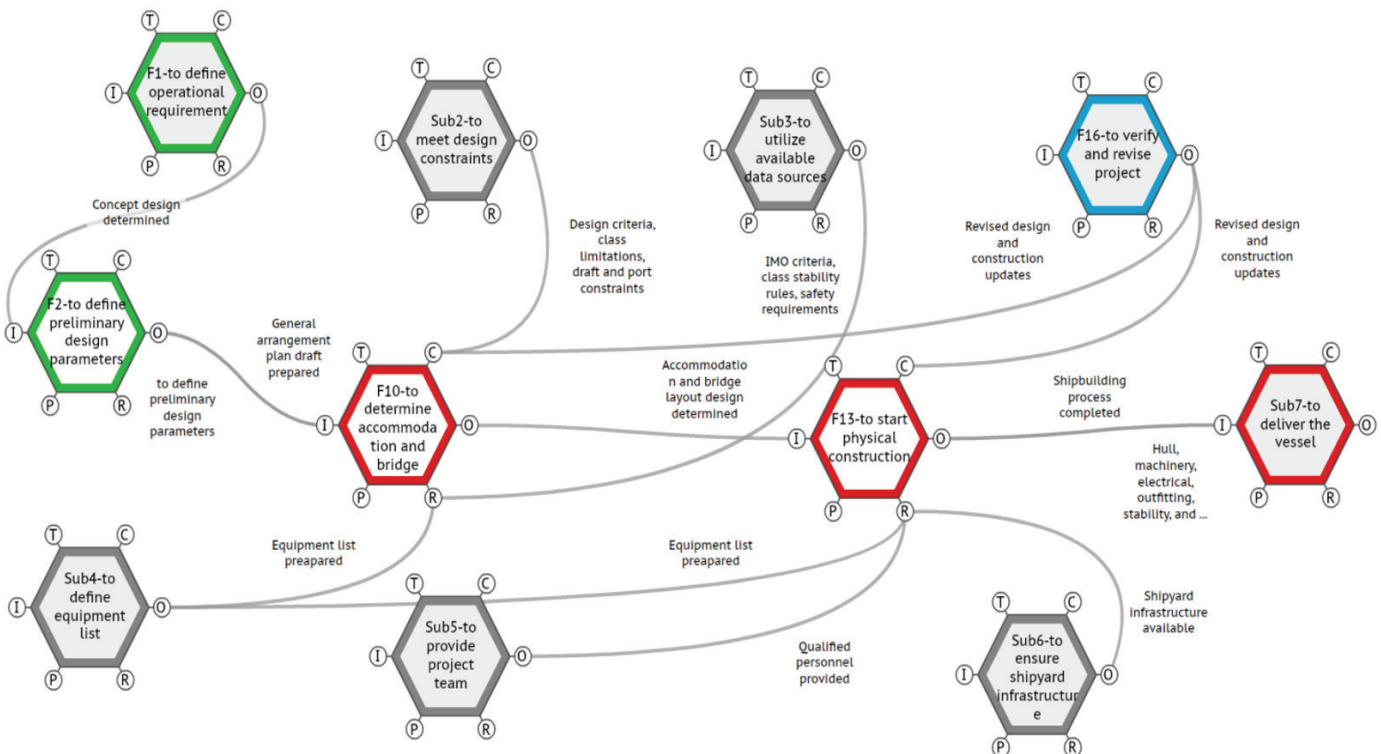


Figure 8. Functional resonance pathway associated with the HVAC problem.

Equipment and material selection deficiency problems originated from accumulated variability among equipment definition, compliance with classification rules, physical construction, and project verification functions. Equipment installation errors emerged as a result of accumulated variability among equipment selection, utilization of design data, physical construction, and verification functions. The insufficient chain-locker capacity problem originated from accumulated variability among deck equipment arrangement, equipment definition, physical construction, and Project verification functions. Alarm monitoring system failures emerged not as isolated equipment malfunctions, but rather as a result of accumulated variability among equipment selection, system integration, verification, and physical construction functions. Accommodation layout problems originated from aggregated variability among accommodation arrangement, design constraints, physical construction, and verification functions. Deck equipment integration deficiencies emerged as a result of accumulated variability among bollard-pull requirements, deck equipment arrangement, equipment selection, physical construction, and verification functions. High vibration complaints emerged as a result of accumulated variability among propulsion system selection, machinery arrangement, project verification, production quality, shipyard infrastructure, and project team capability functions.

With scope of the FRAM analysis, the effects of variability on the entire system were taken into consideration. Although the ultimate objective was the smooth delivery of the vessel and the minimization of failures during the warranty period, it was observed that this objective could not be achieved in the investigated case.

Similarly, the variability aggregation pathway for other problems as:

- Equipment and material selection deficiency:
F1→F2→Sub4→F14→F13→F16→Sub7.
- Equipment installation errors:
F1→F2→Sub4→Sub3 →F13→F16→Sub7.
- Insufficient chain-locker capacity:
F1→F2→F9→Sub4→F13→F16→Sub7.
- Alarm monitoring system failures:
F1→F2→Sub4→F12→F13→F16→Sub7.
- Accommodation-layout problems:
F1→F2→F10→Sub2→F13→F16→Sub7.
- Deficiencies in deck-equipment arrangement:
F1→F2→F8→F9→Sub4→F13→F16→Sub7.
- High vibration complaints:
F1→F2→F4→F5→F11→F16→F13→Sub6/Sub5→Sub7.

3.2. Transformation of Functional Variability into Fuzzy FMEA Failure Modes

The FRAM analysis revealed that the problems observed in the investigated tugboat case originated from triggered

functional variabilities. Therefore, the outputs obtained from the FRAM variability aggregation pathways were transformed into failure modes and evaluated using the Fuzzy FMEA methodology as presented in Table 9. FRAM was first applied to identify variability propagation pathways within the tugboat design and construction processes. The identified variability-induced failure modes were then assessed using fuzzy FMEA to determine their criticality and risk priority levels.

3.3. Fuzzy FMEA Analysis

Following the FRAM-based functional variability analysis, fuzzy FMEA was conducted in order to semi-quantitatively evaluate the risks associated with the identified functional variabilities and potential failure modes. The integration of FRAM and fuzzy FMEA enabled both the identification of variability propagation mechanisms and the prioritization of the associated risks under uncertainty conditions. Within the scope of the analysis, potential failure modes derived from the FRAM model were systematically evaluated by considering design, production, operational, and organizational aspects of tugboat design and construction processes. Unlike conventional FMEA approaches relying mainly on historical failure records, the proposed method also considers functional couplings and variability propagation under uncertainty conditions.

The analysis process consisted of several methodological stages, including the identification of failure modes (Table 9), expert evaluations, transformation of linguistic assessments into fuzzy numbers (Table 10), aggregation of expert opinions, calculation of the *FRPN*, and defuzzification of the obtained results (Table 11). The experts assessed each failure mode in terms of occurrence probability, severity of consequences, and detectability using predefined linguistic scales. Due to the inherent uncertainty and subjectivity of expert judgments, triangular fuzzy numbers were utilized to model the evaluation process. The obtained fuzzy risk values were subsequently defuzzified to determine crisp *FRPN* values, enabling the prioritization of critical failure modes. Accordingly, the proposed framework enabled the identification and prioritization of critical technical and organizational vulnerabilities within tugboat design and construction processes.

The risk-level ranges were defined based on the theoretical *FRPN* scale of 0-1000 and expert judgment, with higher ranges representing risks requiring greater priority and more immediate corrective action. According to Table 12, risk thresholds were classified as follows: very high ≥ 500 ; high ≥ 350 ; moderately high ≥ 200 ; moderate ≥ 100 ; low < 100 . The calculated *FRPN* values and corresponding risk rankings of the identified failure modes are presented in Table 13.

Table 9. Potential function output variability.

No	Functional variability	Failure mode	Effect
F1V1	Inconsistencies in operational preferences	Incompatible operational design basis	Design-operation mismatch
F1V2	Failure of the vessel to fully meet its intended construction purpose	Operational requirement deficiency	Operational performance loss
F2V3	Preliminary design stage was not carried out properly	Preliminary design mismatch	Propulsion-system integration constraints
F2V4	Errors and deficiencies in analyses and engineering calculations	Incorrect engineering calculations	Design-verification problems
F4V5	Main engine-propulsion system integration was not sufficiently controlled	Limited propulsion integration flexibility	Increased shaft-angle susceptibility
F5V6	Propulsion system is not compatible with the hull	Hull-propulsion system incompatibility	Main engine-ASD alignment difficulty
F5V7	Installation errors exist in the propulsion system	Propulsion-system alignment deficiency	Vibration propagation
F5V8	Reduction in propulsion efficiency due to additional shaft arrangement	Cardan shaft dependency	Propulsion efficiency loss
F8V9	Operational deficiencies caused by deck arrangement	Bollard-pull integration pressure	Operational usability constraints
F9V10	Excessive limitations in anchoring and mooring operations	Insufficient chain-locker capacity	Towing-operation limitation
F9V11	Improper towing hook/winch/chain-locker arrangement	Deck-equipment integration inconsistency	Inefficiency in deck operations
F10V12	Errors in accommodation-space arrangement	Accommodation-layout incompatibility	Crew comfort loss
F10V13	Insufficient and improper ventilation circuit installation	HVAC outfitting deficiency	HVAC condensation and leakage
F11V14	Accessibility difficulties due to equipment arrangement	Engine-room arrangement mismatch	Maintenance and accessibility difficulties
F11V15	Errors and deficiencies in piping/circuit installations	Difficulty in accessing piping/circuits	Extended repair time and system unavailability
F12V16	Constraints exist in engine-room equipment arrangement	Safety-system integration constraint	Operational safety weakness
F12V17	Excessive number of alarms in the alarm monitoring system	Alarm-system integration instability	Monitoring and control deficiencies
F13V18	Incomplete and improper installations exist	Construction-stage implementation deviation	Repetitive operational failures
F13V19	Excessive number of rework activities	Inadequate production coordination	Loss of construction efficiency
F13V20	Poor workmanship quality	Low production quality	Construction-quality problems
F13V21	Construction process did not progress according to the planned schedule	Construction-process delay	Extension of vessel delivery period
F14V22	Insufficient inspection and supervision by the classification society	Classification inspection deficiency	Incomplete nonconformity detection
F14V23	Incorrect implementation of classification rules	Improper classification practices	Operational incompatibility
F14V24	Construction progressed without considering classification rules	Classification compliance deficiency	Certification and safety problems
F15V25	Lack of coordination between departments	Organizational communication deficiency	Construction coordination problems
F15V26	Shipyard organizational units are not of sufficient quality	Organizational management deficiency	Production quality loss

Table 9. Continued.

No	Functional variability	Failure mode	Effect
F16V27	Insufficient follow-up of revision works	Project-verification insufficiency	Incomplete corrective actions
F16V28	Incomplete and improper inspections exist	System-validation insufficiency	Repetitive operational nonconformities
Sub1V29	Errors in the selection of the vessel's main characteristic dimensions	Main characteristic design incompatibility	Hull-system integration problems
Sub2V30	Design constraints were incorrectly interpreted	Design-constraint interpretation error	Integration and arrangement problems
Sub3V31	Previous project data were incorrectly applied to the new project	Design-data interpretation inconsistency	Local design adaptation error
Sub4V32	Improper equipment and material selections exist	Improper equipment/material selection	System incompatibility
Sub4V33	Delays occurred in the delivery of equipment to the shipyard	Critical equipment procurement delay	Construction-process delay
Sub5V34	Engineering team is insufficient	Engineering-team capability limitation	Insufficient engineering supervision
Sub5V35	Quality-control activities are insufficient	Quality-control deficiency	Operational quality problems
Sub6V36	Shipyard infrastructure is insufficient	Shipyard infrastructure limitation	Reduced construction quality
Sub6V37	Vessel construction in a location remote from material logistics and qualified workforce resources	Shipyard logistics and workforce accessibility limitation	Delays in construction activities and reduced production quality
Sub7V38	Vessel was delivered with existing failures	Operational transfer instability	High warranty-period deficiency reports
Sub7V39	Excessive failure reports during warranty period	Aggregated functional resonance	Operational reliability loss
Sub7V40	Delay in vessel delivery date	Delivery-process delay	Operational planning loss

3.4. Sensitivity and Uncertainty Analysis

The robustness of the results was examined in terms of expert agreement, individual expert influence, and changes in the O-S-D weights. The results are summarized in Table 14.

4. Results and Discussion

According to the Fuzzy FMEA results, the highest-ranked functional variability was identified as F5V6 with an *FRPN* value of 622.667 related to the failure mode “hull-propulsion system incompatibility.” The second-ranked variability was identified as Sub7V39 with an *FRPN* value of 525.765 related to the failure mode “aggregated functional resonance.” F16V28 ranked third with an *FRPN* value of 483.984 related to the failure mode “system-validation insufficiency.” F4V5 was identified as the fourth-ranked variability with an *FRPN* value of 473.675 related to the failure mode “limited propulsion integration flexibility.” F5V7 ranked fifth with an *FRPN* value of 447.952 related to the failure mode “propulsion-system alignment deficiency.” In addition, F14V24 ranked sixth with an *FRPN* value of 441.760 related to the failure mode “classification compliance deficiency,” Sub5V34 was identified as the seventh-ranked variability

with an *FRPN* value of 438.843 related to the failure mode “engineering-team capability limitation,” Sub7V38 ranked eighth with an *FRPN* value of 424.083 related to the failure mode “operational transfer instability,” Sub5V35 ranked ninth with an *FRPN* value of 417.904 related to the failure mode “quality-control deficiency.” Finally, F11V15 was identified as the tenth-ranked variability with an *FRPN* value of 396.965 related to the failure mode “difficulty in accessing piping/circuits.”

Figure 9 presents the distribution of the average *FRPN* values of the main and sub-functions identified within the scope of the investigated tugboat case. The results indicate that the highest functional risk contribution is related to the propulsion-system selection function (F5). This is followed respectively by the main engine power determination (F4), preliminary design parameter definition (F2), and project verification and revision (F16) functions. In addition, organizational and support functions such as project-team capability (Sub5), shipyard infrastructure (Sub6), and vessel delivery process (Sub7) are also observed to have significant functional risk contributions.

Table 10. Experts' linguistic evaluations.

Code	O_E1	S_E1	D_E1	O_E2	S_E2	D_E2	O_E3	S_E3	D_E3	O_E4	S_E4	D_E4	O_E5	S_E5	D_E5
F1V1	M	MOD	M	M	H	MH	H	H	M	M	MOD	L	M	H	M
F1V2	M	H	M	H	H	L	H	VH	L	H	H	L	H	VH	M
F2V3	H	H	L	H	VH	L	H	VH	VL	H	H	L	H	VH	M
F2V4	M	H	L	H	VH	VL	H	VH	VL	M	H	L	H	VH	M
F4V5	H	VH	VL	H	HAZ	R	VH	HAZ	R	H	VH	VL	H	HAZ	L
F5V6	H	HAZ	R	VH	HAZ	R	VH	CAT	VR	H	HAZ	R	VH	CAT	VL
F5V7	H	VH	L	H	HAZ	VL	VH	HAZ	R	H	VH	L	H	HAZ	VL
F5V8	H	H	M	H	VH	L	H	VH	L	M	H	M	H	VH	L
F8V9	M	MOD	M	H	H	M	M	H	L	H	H	M	H	H	L
F9V10	M	H	M	H	H	L	H	VH	L	H	H	M	H	VH	L
F9V11	M	MOD	M	H	H	M	H	H	L	M	H	M	H	H	L
F10V12	H	MOD	M	H	H	L	H	H	L	M	H	M	H	H	L
F10V13	H	H	M	VH	H	L	VH	VH	L	H	H	M	VH	VH	L
F11V14	M	MOD	M	H	H	M	H	H	L	M	H	M	H	H	L
F11V15	H	H	L	H	VH	VL	VH	VH	R	H	H	L	H	VH	VL
F12V16	M	H	M	H	H	L	H	VH	L	M	H	M	H	VH	L
F12V17	H	MOD	M	VH	H	L	VH	H	L	H	H	M	VH	H	L
F13V18	H	H	M	VH	VH	L	VH	VH	L	H	H	M	VH	VH	L
F13V19	H	MOD	M	H	H	L	VH	H	L	H	MOD	M	H	H	L
F13V20	H	H	L	VH	H	L	VH	VH	VL	H	H	L	H	VH	M
F13V21	H	MOD	H	H	H	M	VH	H	M	H	H	H	H	H	M
F14V22	M	H	VL	H	VH	R	H	VH	R	M	H	VL	H	VH	L
F14V23	M	H	VL	H	VH	R	H	VH	R	M	H	VL	H	VH	L
F14V24	M	VH	R	H	HAZ	R	H	HAZ	VR	M	VH	R	H	HAZ	VL
F15V25	H	MOD	M	H	H	L	VH	H	L	H	H	M	H	H	L
F15V26	H	H	M	VH	H	L	VH	VH	VL	H	H	M	VH	VH	L
F16V27	H	H	L	H	VH	VL	VH	VH	R	H	H	L	H	VH	VL
F16V28	H	VH	L	VH	VH	VL	VH	HAZ	R	H	VH	L	VH	HAZ	VL
Sub1V29	M	H	L	H	H	VL	H	VH	VL	M	H	L	H	VH	M
Sub2V30	H	H	L	H	VH	VL	VH	VH	R	H	H	L	H	VH	VL
Sub3V31	H	H	L	H	VH	VL	H	VH	R	M	H	L	H	VH	VL
Sub4V32	H	H	M	H	H	L	VH	VH	L	H	H	M	H	VH	L
Sub4V33	H	MOD	H	H	H	M	VH	H	M	H	MOD	H	H	H	M
Sub5V34	H	H	L	VH	VH	VL	VH	VH	R	H	H	L	VH	VH	VL
Sub5V35	H	H	L	VH	VH	VL	VH	VH	R	H	H	L	H	VH	VL
Sub6V36	H	H	M	VH	VH	L	VH	VH	VL	H	H	M	VH	VH	L
Sub6V37	H	MOD	M	VH	H	L	VH	H	L	H	H	M	VH	H	L
Sub7V38	H	VH	M	VH	HAZ	L	VH	HAZ	VL	H	VH	M	VH	HAZ	L
Sub7V39	VH	VH	L	VH	HAZ	VL	VH	CAT	R	H	VH	L	VH	HAZ	VL
Sub7V40	H	MOD	H	H	H	M	VH	H	M	H	H	H	H	H	M

Table 11. Defuzzification.

Code	O_a	S_m	D_b	O_a	S_m	D_b	O_a	S_m	D_b	FRPN_a	FRPN_m	FRPN_b
F1V1	4.40	5.60	4.00	5.40	6.60	5.00	6.40	7.60	6.00	98.560	178.200	291.840
F1V2	5.60	6.40	4.60	6.60	7.40	5.60	7.60	8.40	6.60	164.864	273.504	421.344
F2V3	6.00	6.60	5.00	7.00	7.60	6.00	8.00	8.60	7.00	198.000	319.200	481.600
F2V4	5.20	6.60	5.20	6.20	7.60	6.20	7.20	8.60	7.20	178.464	292.144	445.824
F4V5	6.40	7.60	6.20	7.40	8.60	7.20	8.40	9.60	8.20	301.568	458.208	661.248
F5V6	7.20	8.40	7.00	8.20	9.40	8.00	9.20	10.00	9.00	423.360	616.640	828.000
F5V7	6.40	7.60	5.80	7.40	8.60	6.80	8.40	9.60	7.80	282.112	432.752	628.992
F5V8	5.60	6.60	4.60	6.60	7.60	5.60	7.60	8.60	6.60	170.016	280.896	431.376
F8V9	5.20	5.80	4.40	6.20	6.80	5.40	7.20	7.80	6.40	132.704	227.664	359.424
F9V10	5.60	6.40	4.60	6.60	7.40	5.60	7.60	8.40	6.60	164.864	273.504	421.344
F9V11	5.20	5.80	4.40	6.20	6.80	5.40	7.20	7.80	6.40	132.704	227.664	359.424
F10V12	5.60	5.80	4.60	6.60	6.80	5.60	7.60	7.80	6.60	149.408	251.328	391.248
F10V13	7.20	6.40	4.60	8.20	7.40	5.60	9.20	8.40	6.60	211.968	339.808	510.048
F11V14	5.20	5.80	4.40	6.20	6.80	5.40	7.20	7.80	6.40	132.704	227.664	359.424
F11V15	6.40	6.60	5.80	7.40	7.60	6.80	8.40	8.60	7.80	244.992	382.432	563.472
F12V16	5.20	6.40	4.60	6.20	7.40	5.60	7.20	8.40	6.60	153.088	256.928	399.168
F12V17	7.20	5.80	4.60	8.20	6.80	5.60	9.20	7.80	6.60	192.096	312.256	473.616
F13V18	7.20	6.60	4.60	8.20	7.60	5.60	9.20	8.60	6.60	218.592	348.992	522.192
F13V19	6.40	5.60	4.60	7.40	6.60	5.60	8.40	7.60	6.60	164.864	273.504	421.344
F13V20	6.80	6.40	5.00	7.80	7.40	6.00	8.80	8.40	7.00	217.600	346.320	517.440
F13V21	6.40	5.80	3.20	7.40	6.80	4.20	8.40	7.80	5.20	118.784	211.344	340.704
F14V22	5.20	6.60	6.20	6.20	7.60	7.20	7.20	8.60	8.20	212.784	339.264	507.744
F14V23	5.20	6.60	6.20	6.20	7.60	7.20	7.20	8.60	8.20	212.784	339.264	507.744
F14V24	5.20	7.60	7.00	6.20	8.60	8.00	7.20	9.60	9.00	276.640	426.560	622.080
F15V25	6.40	5.80	4.60	7.40	6.80	5.60	8.40	7.80	6.60	170.752	281.792	432.432
F15V26	7.20	6.40	4.80	8.20	7.40	5.80	9.20	8.40	6.80	221.184	351.944	525.504
F16V27	6.40	6.60	5.80	7.40	7.60	6.80	8.40	8.60	7.80	244.992	382.432	563.472
F16V28	7.20	7.40	5.80	8.20	8.40	6.80	9.20	9.40	7.80	309.024	468.384	674.544
Sub1V29	5.20	6.40	5.20	6.20	7.40	6.20	7.20	8.40	7.20	173.056	284.456	435.456
Sub2V30	6.40	6.60	5.80	7.40	7.60	6.80	8.40	8.60	7.80	244.992	382.432	563.472
Sub3V31	5.60	6.60	5.80	6.60	7.60	6.80	7.60	8.60	7.80	214.368	341.088	509.808
Sub4V32	6.40	6.40	4.60	7.40	7.40	5.60	8.40	8.40	6.60	188.416	306.656	465.696
Sub4V33	6.40	5.60	3.20	7.40	6.60	4.20	8.40	7.60	5.20	114.688	205.128	331.968
Sub5V34	7.20	6.60	5.80	8.20	7.60	6.80	9.20	8.60	7.80	275.616	423.776	617.136
Sub5V35	6.80	6.60	5.80	7.80	7.60	6.80	8.80	8.60	7.80	260.304	403.104	590.304
Sub6V36	7.20	6.60	4.80	8.20	7.60	5.80	9.20	8.60	6.80	228.096	361.456	538.016
Sub6V37	7.20	5.80	4.60	8.20	6.80	5.60	9.20	7.80	6.60	192.096	312.256	473.616
Sub7V38	7.20	7.60	4.80	8.20	8.60	5.80	9.20	9.60	6.80	262.656	409.016	600.576
Sub7V39	7.60	7.80	5.80	8.60	8.80	6.80	9.60	9.60	7.80	343.824	514.624	718.848
Sub7V40	6.40	5.80	3.20	7.40	6.80	4.20	8.40	7.80	5.20	118.784	211.344	340.704

Table 12. Failures' risk level color scale.

Crisp <i>FRPN</i> range	Risk level	Scale
$FRPN \geq 500$	Very high	
$350 \leq FRPN < 500$	High	
$200 \leq FRPN < 350$	Moderately high	
$100 \leq FRPN < 200$	Moderate	
$FRPN < 100$	Low	

As presented in Table 15, the comparison between warranty-period deficiency records and the FRAM-Fuzzy FMEA results indicates that the highest-ranked variability-induced failure modes correspond well with the major operational problems observed during the vessel's warranty period. In particular, propulsion-system integration deficiencies, verification shortcomings, HVAC-related failures, alarm-monitoring system instabilities, and accommodation-layout problems were identified both in the operational records and in the *FRPN* prioritization results. These findings provide practical validation of the proposed FRAM-Fuzzy FMEA framework under real shipbuilding and operational conditions.

According to the results, failure modes related to the propulsion system were found to have the highest perceived risk levels (F5V6, F4V5, and F5V7). High maneuverability is one of the fundamental performance requirements that must be achieved in tugboats for operational success [72]. Particularly during active escort operations, a tugboat is expected to perform under high dynamic loads without compromising either its own safety or the safety of the assisted vessel. The compatibility between main engine power, propulsion system characteristics, and hull form plays a decisive role in achieving this performance. Incompatibilities among these elements may lead to deficiencies in bollard pull capacity, maneuverability, and overall operational performance. Furthermore, reductions in propulsion efficiency may adversely affect service quality, while vibration-related problems may negatively influence both crew working conditions and equipment reliability. Therefore, the experts evaluated hull-propulsion system incompatibility as a critical failure modes that may affect multiple functions in the later stages of the design process and lead to significant operational consequences, and consequently ranked it as the variability with the highest perceived risk.

The objective of ship design is to construct vessels that comply with safe navigation standards. Negative variabilities occurring from the beginning of the design process to the final stage affect the vessel delivery process. During delivery, failures and deficiencies that do not affect the vessel's floatability or navigation safety are generally

rectified through warranty processes. However, failures and deficiencies related to propulsion performance, insufficient bollard pull, structural systems, stability, piping arrangements, and similar systems may lead to delivery delays and major revisions [73]. Therefore, it is essential that failures and deficiencies are identified and eliminated throughout the entire process before reaching the delivery stage. For this reason, major failures and deficiencies at the delivery stage (Sub7V39) were evaluated by the experts as a high-risk failure mode.

Although classification rules are clearly defined, deficiencies may still occur during their implementation in the design and physical construction stages. Such deficiencies must be eliminated through appropriate revisions. At this point, cost and schedule pressures may lead to certain requirements being overlooked or interpreted incompletely. Furthermore, the failure of plan approval and quality control departments to detect these deficiencies may result in revision processes being bypassed. This situation increases functional variability negatively during tugboat delivery. Therefore, the failure mode (F14V24, F16V28), associated with the function of verification of design and construction and revision of deficiencies, was evaluated by the experts as having a high perceived risk level.

Failure modes generated by variabilities originating from organizational functions were generally perceived by the experts as an important source of risk (Sub5V34, Sub5V35). These findings indicate that human and organizational factors play a significant role in the design and construction process [74]. Even when technical design procedures are well defined, insufficient expertise, communication deficiencies, or inadequate quality assurance practices may increase functional variability throughout the design process and consequently affect the vessel delivery process.

For sensitivity and uncertainty the Kendall's *W* results indicated significant agreement among the experts for occurrence ($W=0.689$), severity ($W=0.872$), and detection ($W=0.805$), with $p < 0.001$ in all cases. In the LOEO analysis, Spearman's correlation coefficients ranged from 0.991 to 0.998, while the maximum rank shift ranged from two to four positions. Under the alternative weighting scenarios, the correlations ranged from 0.961 to 0.992. The largest rank

Table 13. Failures' *FRPN* values and risk rankings.

Code	Crisp <i>FRPN</i>	Rank	Risk level
F1V1	189.533	40	Moderate
F1V2	286.571	29	Moderately High
F2V3	332.933	21	Moderately High
F2V4	305.477	25	Moderately High
F4V5	473.675	4	High
F5V6	622.667	1	Very High
F5V7	447.952	5	High
F5V8	294.096	28	Moderately High
F8V9	239.931	34	Moderately High
F9V10	286.571	29	Moderately High
F9V11	239.931	34	Moderately High
F10V12	263.995	33	Moderately High
F10V13	353.941	18	High
F11V14	239.931	34	Moderately High
F11V15	396.965	10	High
F12V16	269.728	32	Moderately High
F12V17	325.989	22	Moderately High
F13V18	363.259	15	High
F13V19	286.571	29	Moderately High
F13V20	360.453	16	High
F13V21	223.611	37	Moderately High
F14V22	353.264	19	High
F14V23	353.264	19	High
F14V24	441.760	6	High
F15V25	294.992	27	Moderately High
F15V26	366.211	14	High
F16V27	396.965	10	High
F16V28	483.984	3	High
Sub1V29	297.656	26	Moderately High
Sub2V30	396.965	10	High
Sub3V31	355.088	17	High
Sub4V32	320.256	24	Moderately High
Sub4V33	217.261	39	Moderately High
Sub5V34	438.843	7	High
Sub5V35	417.904	9	High
Sub6V36	375.856	13	High
Sub6V37	325.989	22	Moderately High
Sub7V38	424.083	8	High
Sub7V39	525.765	2	Very High
Sub7V40	223.611	37	Moderately High

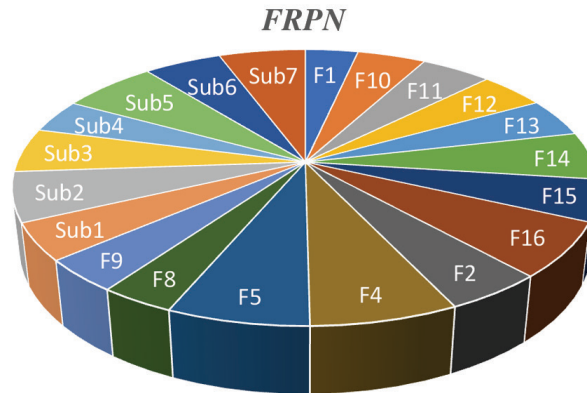


Figure 9. Distribution of average *FRPN* values according to functional variabilities.

Table 14. Failures' *FRPN* values and risk rankings.

Analysis	Criterion/scenario	Spearman's ρ	Maximum rank shift
Expert agreement	Occurrence	$W=0.689$	-
Expert agreement	Severity	$W=0.872$	-
Expert agreement	Detection	$W=0.805$	-
LOEO analysis	Exclusion of E1-E5	$\rho=0.991-0.998$	2-4
Weight sensitivity	O-dominant (0.50, 0.25, 0.25)	$\rho=0.961$	11
Weight sensitivity	S-dominant (0.25, 0.50, 0.25)	$\rho=0.992$	4
Weight sensitivity	D-dominant (0.25, 0.25, 0.50)	$\rho=0.977$	7

Table 15. Comparison of warranty-period deficiencies and FRAM-Fuzzy FMEA results.

Operational deficiency observed during warranty	Variability	Failure mode	<i>FRPN</i> rank
Propulsion system vibration and bearing overheating	F5V6	Hull-propulsion system incompatibility	1
Multiple deficiencies accumulated at delivery	Sub7V39	Aggregated functional resonance	2
Repetitive operational non-conformities	F16V28	System-validation insufficiency	3
Main engine-ASD integration problems	F4V5	Limited propulsion integration flexibility	4
Propulsion alignment and vibration problems	F5V7	Propulsion-system alignment deficiency	5
Classification and compliance deficiencies	F14V24	Classification compliance deficiency	6
Engineering supervision limitations	Sub5V34	Engineering-team capability limitation	7
Vessel delivered with existing failures	Sub7V38	Operational transfer instability	8
Insufficient quality-control activities	Sub5V35	Quality-control deficiency	9
Errors and deficiencies in piping/circuit installations	F11V15	Difficulty in accessing piping/circuits	10
HVAC condensation and leakage	F10V13	HVAC outfitting deficiency	18
Alarm monitoring system deficiencies	F12V17	Alarm-system integration instability	22
Improper equipment/material selection	Sub4V32	Improper equipment/material selection	24
Chain-locker capacity deficiency	F9V10	Insufficient chain-locker capacity	29
Accommodation-layout deficiencies	F10V12	Accommodation-layout incompatibility	33

shift occurred in the occurrence-dominant scenario. Overall, the results indicate that the *FRPN* ranking is stable, although it is relatively more sensitive to changes in occurrence weighting.

The results indicate that risk mitigation efforts should primarily focus on propulsion system selection and hull integration, construction control and verification activities, and the organizational capability of the shipyard. It can be observed that risk perception is mainly shaped in areas where failure modes originating from human, technological, and organizational factors intersect. In the case study, the FRAM method identified the areas where variability accumulated in a negative manner. These areas essentially represent the reference points where risk-reducing control measures should be implemented. During the design process, the integration of the propulsion system and hull should be verified through calculations, model studies, and previous projects. Calculations should be reviewed again in accordance with any changes in principal dimensions. The integration process

of new orders with ongoing construction projects should be managed through detailed control checklists. Based on the findings of the study, the recommended risk mitigation and control measures for reducing the identified critical risks are presented in the following Figure 10. Risk control measures generally consist of monitoring, planning, anticipating, and supporting activities [75].

Since the tugboat design and construction process was systematically and functionally defined using the FRAM method, the development of practical control checklists may contribute to the management of variability and the early identification of risks. In addition, storing project information and progress details in cloud-based systems may enable rapid reviews and monitoring whenever required. In this regard, the development of a cloud-based platform covering the entire construction process could facilitate the work of project managers by improving control, coordination, and decision-making activities throughout the project lifecycle.

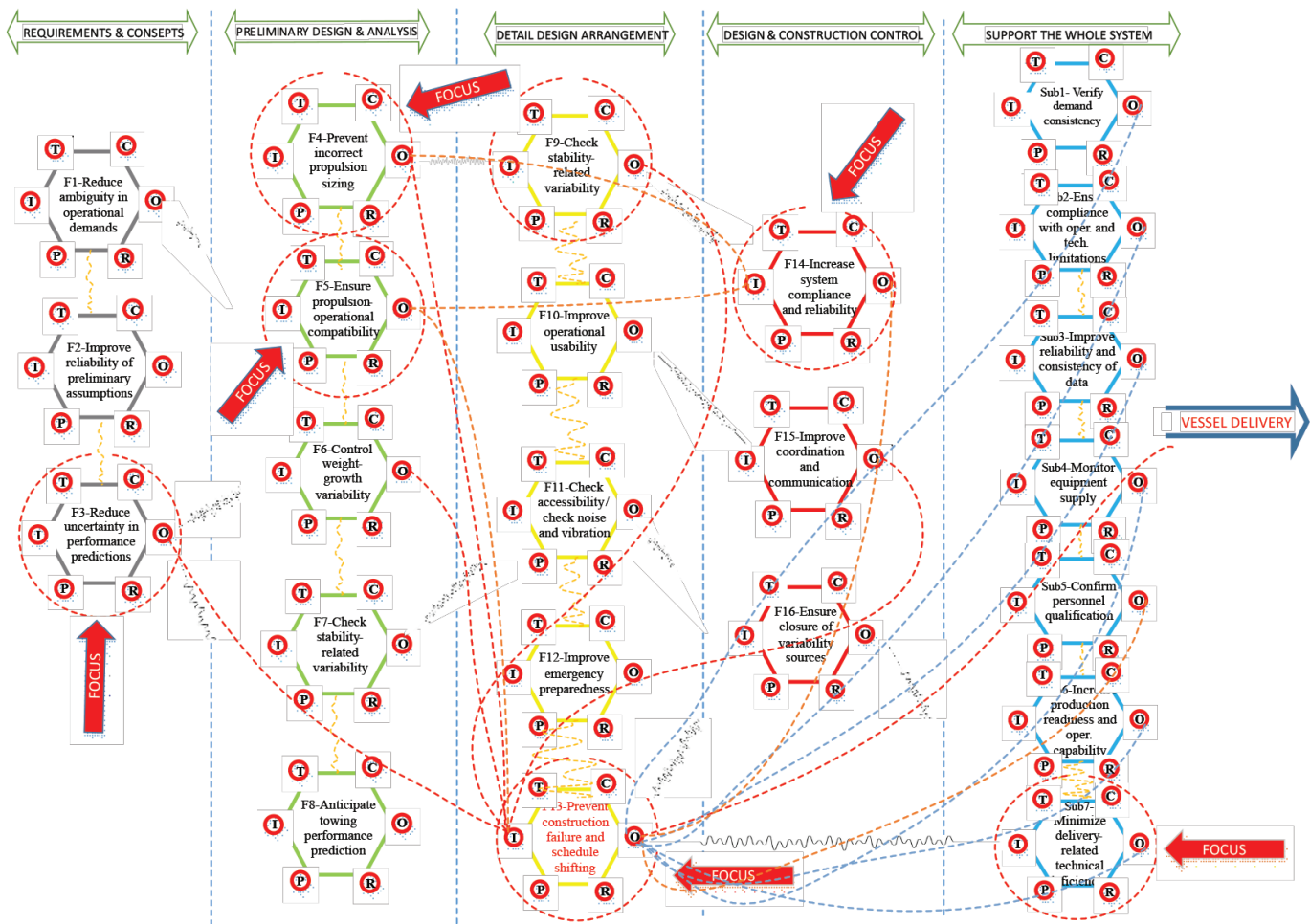


Figure 10. Risk mitigation and control measures.

5. Conclusion

This study presents an integrated FRAM-Fuzzy FMEA framework to evaluate functional variability and risk propagation within tugboat design and shipbuilding processes from a resilience-oriented systems perspective. Unlike conventional linear risk-assessment approaches, the methodology considers tugboat design and shipbuilding as a complex socio-technical system in which technical calculations, operational requirements, production activities, classification-society compliance processes, and organizational interactions continuously influence each other. Through the FRAM analysis, the functional relationships among design phases, main engine and propulsion system selection, stability verification, general and deck equipment arrangement, physical construction, shipbuilding organization with all sub-activities, revision-management processes and ship delivery were systematically modeled. The findings demonstrated that variability generated during early design stages may propagate throughout subsequent engineering, production, and verification activities, thereby creating system-wide variability effects. In particular, operational requirement definition, hull-main engine-propulsion compatibility, revision-management processes, engineering team, quality performance, classification and communication of shipyard departments, and ship delivery were identified as critical functions with high variability potential.

The results showed that propulsion system incompatibilities, aggregation of negative variability on ship delivery and project validation insufficiency, and coordination failures between design and production units constitute the most critical risk areas within tugboat projects. The findings further demonstrated that organizational and communication-related deficiencies may become as critical as technical engineering failures in complex maritime systems. Accordingly, the study revealed that risk formation within tugboat projects emerges not only from isolated technical failures, but also from the interaction, aggregation, and propagation of functional variabilities across interconnected system functions.

The integration of FRAM and Fuzzy FMEA enabled the transformation of qualitative functional variability into semi-quantitative risk prioritization. In this respect, the framework provides a proactive, resilience-oriented, and system-based safety assessment approach for tugboat design and shipbuilding processes. From a practical perspective, the framework may support shipyards, designers, shipowners, and classification stakeholders in identifying critical variability sources during early-stage design, verification, and production-planning activities. The framework enables the early identification of critical variability

pathways associated with propulsion-system integration, accommodation and HVAC arrangements, classification compliance, organizational coordination, and project-verification activities. By prioritizing variability-induced failure modes according to their *FRPN* values, engineering resources, inspection efforts, and quality-control activities can be allocated more effectively. Consequently, potential design deficiencies, integration problems, and coordination weaknesses may be detected before they evolve into costly rework activities, warranty-period deficiencies, operational failures, or project delays. Furthermore, the study demonstrated that strengthening monitoring capability, technical verification procedures, revision management, and interdisciplinary coordination may significantly reduce variability propagation and improve overall system reliability. Accordingly, the proposed framework may contribute to improving construction quality, reducing warranty-period deficiencies, enhancing operational safety, and supporting the timely delivery of vessels with increased reliability.

Although the construction functions were defined to represent the general tugboat design and construction process, the empirical analysis was based on a single 70-ton bollard-pull ASD tug and five experts. Therefore, the *FRPN* values and risk rankings may be influenced by project-specific conditions and the composition of the expert panel, limiting the generalizability of the findings. Future studies should apply the framework to different tugboat types and shipyards using larger and more diverse expert panels.

Future studies may further improve the framework through the integration of real-time operational and maneuvering data obtained from harbor tug operations, including escort towing conditions, indirect towing forces, dynamic loading effects, and bollard-pull performance variations. In addition, the effects of hybrid and electric propulsion systems, alternative fuel applications, autonomous tugboat concepts, and advanced propulsion arrangements on functional variability and system resilience may be investigated in future research. The proposed methodology may also be expanded through full-scale operational data collection, digital-twin-supported tugboat simulations, and lifecycle-based maintenance analyses. Furthermore, integrating predictive maintenance systems, operational performance monitoring, and human-factor assessments involving tug masters, pilots, and shipyard personnel may further improve the realism and applicability of variability and risk assessments in future tugboat projects.

Footnotes

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