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Exploring Uncertainty in Maritime Collisions: A Qualitative FRAM Approach

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Abstract This study employs the Functional Resonance Analysis Method (FRAM) to investigate the dynamics of maritime collisions characterized by inherent uncertainties and interdependent operational variables. Through qualitative analysis, FRAM can identify functional variabilities within the system and explore how interactions among operational functions contribute to risk accumulation under complex conditions. The analysis highlights critical points where deviations in timing, environmental factors, and human responses intersected, escalating risks and ultimately leading to the collision. Key findings reveal how delayed command actions, communication gaps, and environmental challenges interact to create cascading effects that amplify safety risks in high-stakes scenarios. By capturing these intricate interactions, the study demonstrates FRAM's effectiveness in analyzing systemic risks and emergent behaviors in complex systems. This approach offers insights into the mechanisms by which operational uncertainties compromise safety and highlights the need for resilient navigational systems. The findings enhance the understanding of maritime collision dynamics and highlight FRAM's suitability for analyzing complex incidents in uncertain environments. By addressing these challenges, the study contributes to improving safety protocols and operational resilience, offering valuable perspectives for managing risks in high-stake maritime operations.

Keywords Qualitative Safety Evaluation · Maritime Collision Dynamics · Maritime Accident, Systemic Uncertainties · Navigational Risk · Functional Interactions

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Exploring Uncertainty in Maritime Collisions: A Qualitative FRAM Approach

Introduction

Maritime operations are inherently susceptible to a range of risks, including navigational hazards, unpredictable weather, and operational complexities, which collectively contribute to the occurrence of maritime accidents (Latt, 2024). Despite ongoing advancements in safety regulations and navigational technologies, the persistent incidence of maritime collisions highlights a critical gap in understanding and managing systemic risks within these operations (Güler et al., 2024; Bicen et al., 2021). These accidents often stem from the complex interplay among human, technical, and environmental factors, with human error frequently identified as a major contributor. However, issues like fatigue, communication gaps, and decision-making under pressure demonstrate that traditional approaches may fail to capture the underlying dynamics of such incidents (Sheng et al., 2024).

Risk assessment approaches in maritime safety have traditionally aimed to identify specific causal factors through structured methodologies, such as Fault Tree Analysis (FTA) (Senol, 2024), Event Tree Analysis (ETA) (Daas and Innal, 2023), Bow-tie (BT) Analysis (Papageorgiou et al., 2024), Failure Mode and Effects Analysis (FMEA) (Luo et al., 2024), and Bayesian Networks (BN) (Animah, 2024), which often rely on a mechanistic decomposition of systems and a focus on linear causality (Ay et al., 2022). In contrast, the Functional Resonance Analysis Method (FRAM) offers a holistic approach, examining how interactions among various system components contribute to functional outcomes in both expected and unforeseen ways (Hollnagel, 2017). FRAM enables an understanding of how risks arise nonlinearly through system interdependencies, offering a unique perspective in scenarios with high uncertainty and complex interactions (Zheng et al., 2024).

In this study, FRAM was applied to analyze a maritime accident documented in a Marine Accident Investigation Branch (MAIB) report in which a definitive cause could not be determined due to the complexity and inherent uncertainties of the incident. This study aims to bridge the methodological insights and practical outcomes by demonstrating the application of FRAM in a real-world maritime collision scenario. On the methodological side, the proposed method demonstrates how FRAM can systematically capture functional interactions and variability in uncertain operational environments. From a practical perspective, the findings provide actionable recommendations for improving safety protocols and enhancing maritime resilience. This study leverages FRAM's systemic approach to qualitatively examine how functional components within the accident interact, providing a comprehensive perspective on maritime collision dynamics. By highlighting interdependent factors that traditional methods may overlook, this research aims to contribute valuable insights into maritime safety, emphasizing the need for resilience when managing uncertainties in complex operational systems.

The Functional Resonance Analysis Method (FRAM) distinguishes itself from traditional risk assessment methods by examining how a system functions under varied conditions rather than focusing solely on causal chains (Yu et al., 2024). FRAM explores how daily interactions within a system contribute to functional outcomes, offering insight into how flexibility and resilience can prevent accidents when unexpected challenges arise (Yasue and Sawaragi, 2024; Hollnagel, 2017). Unlike approaches that attribute incidents to single-point failures, FRAM uniquely focuses on how systems operate in practice, shedding light on both expected and unexpected functional interactions. While other systemic approaches, such as STAMP, STPA, and CAST, also consider systemic interactions (Patriarca et al., 2022), FRAM emphasizes the emergent nature of risks and explores how they dynamically resonate within a system, rather than merely tracing causal pathways (Viran and Mentes, 2024). This feature renders FRAM particularly effective for analyzing the dynamic behavior of complex systems under stress (Liu et al., 2024).

FRAM's adaptability has enabled its application across various high-risk industries (Kumar et al., 2024), such as healthcare (Sujan et al., 2024; Saadi et al., 2024), nuclear energy (Fu et al., 2022; Lee and Lee, 2018), aviation (Okine et al., 2024; Tengiz and Unal, 2023; Hollnagel et al., 2008), and rail transport (Rad et al., 2023). In these fields, understanding system dynamics is essential for identifying underlying risks that may not be immediately apparent. FRAM's capacity to reveal intricate interdependencies and emergent risks provides a deeper view of potential failure points within complex operations, especially those that may elude more linear, deterministic methods (Patriarca et al., 2020). Applications in these sectors highlight FRAM's effectiveness in addressing multifaceted operational challenges, offering a holistic approach to risk management and system resilience (Tian and Caponecchia, 2020).

In the maritime sector, FRAM has been employed to address similar complexities, such as operational safety in cargo handling, emergency response coordination, and navigation in constrained waters (Ma et al., 2023). Studies have demonstrated FRAM's capability to account for the intricate interplay among human, technical, and environmental factors in maritime operations, advancing the industry's approach to safety by shifting the focus from isolated causes to a broader view of systemic functionality (Salihoglu and Bal Beşikçi, 2021).

In this study, FRAM was used to investigate a maritime accident where a clear cause could not be identified due to the inherent uncertainties and complexity of the event. This accident, documented in the UK Marine Accident Investigation Branch (MAIB) database, lacked a definitive explanation, presenting an ideal case to explore using FRAM's systemic analysis (MAIB, 2020). By assigning valid data from the MAIB accident report as input variables, FRAM allows for a qualitative examination of the accident, treating each functional component as if it operates independently while contributing to the larger system outcome.

This study's unique contribution lies in its focus on an accident where conventional analyses did not yield a definitive cause. By applying FRAM, this research provides a holistic view of the accident's underlying dynamics, identifying functional interdependencies that traditional methods may overlook. This approach not only contributes to understanding maritime accidents with ambiguous causes but also underscores the importance of systemic resilience in the prevention of future accidents. In doing so, this study offers an innovative approach to maritime safety, enriching the field with insights into handling uncertainties in complex operational systems.

Methodology

This study employs the Functional Resonance Analysis Method (FRAM) to investigate a complex maritime accident characterized by high uncertainty and the absence of a definitive cause. The methodology involves identifying key functions within maritime operation, modeling their interactions using the "FRAM Model Visualizer" (FMV), and examining how variability in these functions affects the system and contributes to control loss and increased risk. By adapting FRAM to address the specific challenges of maritime accidents, this study offers a detailed, qualitative analysis of how complex dynamics within a high-risk operational environment contribute to the outcome of an incident.

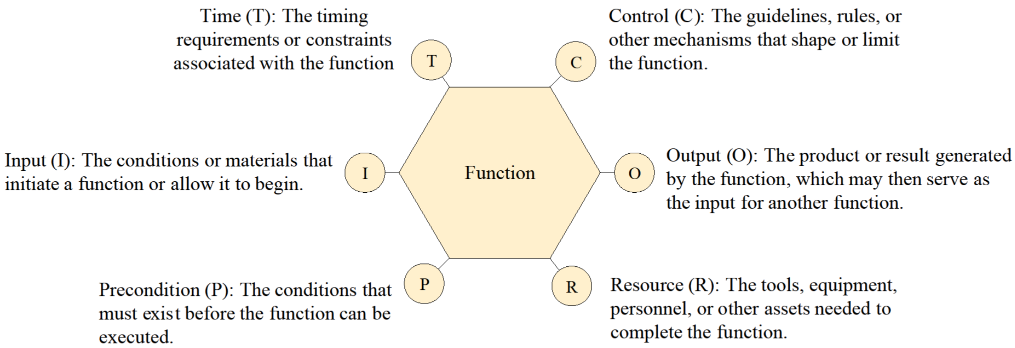
Functional Resonance Analysis Method (FRAM)

The Functional Resonance Analysis Method (FRAM) is a systemic, nonlinear approach to analyze complex sociotechnical systems (Hollnagel, 2013). Developed by Hollnagel, FRAM seeks to understand not only how systems work under normal conditions but also how interactions between system components can lead to accidents when variability is introduced (Hollnagel, 2016). Unlike traditional linear accident analysis methods, which focus on cause-and-effect relationships, FRAM views accidents as emergent outcomes resulting from the interaction of multiple, interdependent functions (Hollnagel and Goteman, 2004). By examining these interactions, FRAM enables analysts to assess where system flexibility can be improved and where risks accumulate, which helps prevent future incidents (Hollnagel, 2017).

A key concept in FRAM is the concept of "functions," which represent the essential tasks or activities within a system that contribute to overall performance. Each function is defined by six aspects: Input, Output, Precondition, Resource, Control, and time (Figure 1 (Herrera and Woltjer, 2010).

Figure 1

Overview of functional aspects of FRAM



By evaluating these six aspects, FRAM revealed how each function interacts with others, especially under variable conditions (Tian et al., 2016). The variability in either of these aspects can propagate through the system, shaping the interactions among functions in ways that amplify certain effects, potentially leading to emergent outcomes. This emergent nature of variability rather than individual failures often results in system breakdowns or accidents in complex settings (Hollnagel, 2017).

FRAM is uniquely suited to modeling and managing variability in complex environments where traditional causality is difficult to establish. It acknowledges that variability in routine operations is natural and sometimes necessary because systems often operate in unpredictable environments (Smith et al., 2017). However, when multiple sources of variability interact and amplify each other—or, conversely, dampen certain impacts—the result can be unexpected and significant. FRAM's focus on these dynamic interactions allows for a more nuanced understanding of risk and resilience, particularly in high-stakes industries, such as healthcare, aviation, nuclear energy, and maritime operations (Patriarca et al., 2020).

In the maritime industry, FRAM has demonstrated effectiveness in capturing the multifaceted interactions between human, technical, and environmental factors that contribute to risk (Praetorius et al., 2011; Tian et al., 2016; Kee, 2017; Lee and Chung, 2018; Salihoglu and Bal Beşikçi, 2021; Qiao et al., 2022; Ma et al., 2023; Yu et al., 2024). By identifying how normal variances can combine and resonate, FRAM facilitates a proactive safety approach that emphasizes the importance of system-wide resilience rather than isolating individual error points (Praetorius et al., 2017). The capacity of FRAM to examine the underlying functional dynamics within systems makes it particularly valuable for accident investigations involving high complexity and uncertain causality.

FRAM Model Visualizer (FMV)

In this study, the "FRAM Model Visualizer" (FMV) was used to construct a detailed FRAM model to analyze the functional interactions involved in maritime accidents. Following model creation, the connections between functions were highlighted manually to represent interactions more clearly, thereby providing a deeper understanding of how the variabilities in one function may propagate through the system.

The FMV, which was written and developed by Rees Hill, is a visual tool based on Hollnagel's FRAM (Hollnagel and Hill, 2020). The proposed platform provides an interactive platform for mapping and analyzing functional interactions, offering valuable analyst support (Patriarca et al., 2017). By representing each function as a hexagon with FRAM's six aspects—Input, Output, Precondition, Resource, Control, and Time—FMV enables analysts to trace how variations in one function influence others, revealing systemic interdependencies that are crucial for understanding risk in complex systems like maritime operations. This visualization approach helps identify potential points where variability in one function may trigger cascading effects, highlighting bottlenecks and hidden dependencies that could affect system stability (Nasur et al., 2025).

In addition to modeling interactions, FMV supports scenario-based modeling, which allows analysts to test different operational conditions to assess potential outcomes. This capability is particularly useful for investigating incidents without a single causative factor, such as the Gülnak and Cape Mathilde accidents examined in this study. By visualizing how variations in specific functions might have contributed to the accident, the FMV offers valuable insights into possible safety interventions and supports a comprehensive understanding of system dynamics, ultimately aiding in the enhancement of safety measures in maritime operations.

Analytical Approach to Complex Maritime Accidents

This study employs FRAM to address the ambiguous and complex nature of the Gülnak–Cape Mathilde collision, which involved a blend of human, technical, and environmental factors. Unlike traditional linear analyses, this systemic approach does not seek a single causative factor but rather examines the layered interactions within the maritime system. FRAM's flexibility allows it to capture the multifaceted interdependencies that characterize maritime operations, especially under uncertain conditions, as highlighted in the Marine Accident Investigation Branch (MAIB) report (Lee et al., 2020).

In this analysis, FRAM focuses on functional interactions and explores potential resonance points rather than direct causal chains. By evaluating how functions like pilot communication, rudder control, and tugboat positioning are performed under variable conditions, this study aims to reveal how minor changes within one function may propagate through the system, escalating the risk (Patriarca and Bergström, 2017). Each function was mapped using FRAM's six aspects (Input, Output, Precondition, Resource, Control, and Time) to visualize how functional variability might influence overall system stability (Praetorius et al., 2017).

A key aspect of this approach is scenario-based modeling, which assesses the reliability of functional aspects, such as the control and resources, during critical stages of the operation. By simulating conditions —such as delays in communication between the bridge team and tugboats—the study evaluates how functional resonance can contribute to adverse outcomes (Yu et al., 2023). This iterative modeling allows continuous refinement of the analysis as new insights are generated, providing a more accurate representation of the accident dynamics (Guo et al., 2023).

Lastly, the analysis identified resonance points where accumulated variabilities among functions led to a loss of operational control, demonstrating that the collision was not the result of a single failure but of a network of interacting functions (Grabbe et al., 2022). This nuanced understanding of accident causation highlights how risks amplify in real-world maritime operations, offering valuable insights into systemic vulnerabilities and informing strategies for safety enhancement and risk mitigation in high-risk maritime environments (Patriarca and Bergström, 2017).

Case Study: Complex Interactions in Gülnak and Cape Mathilde Collision

Accident Description

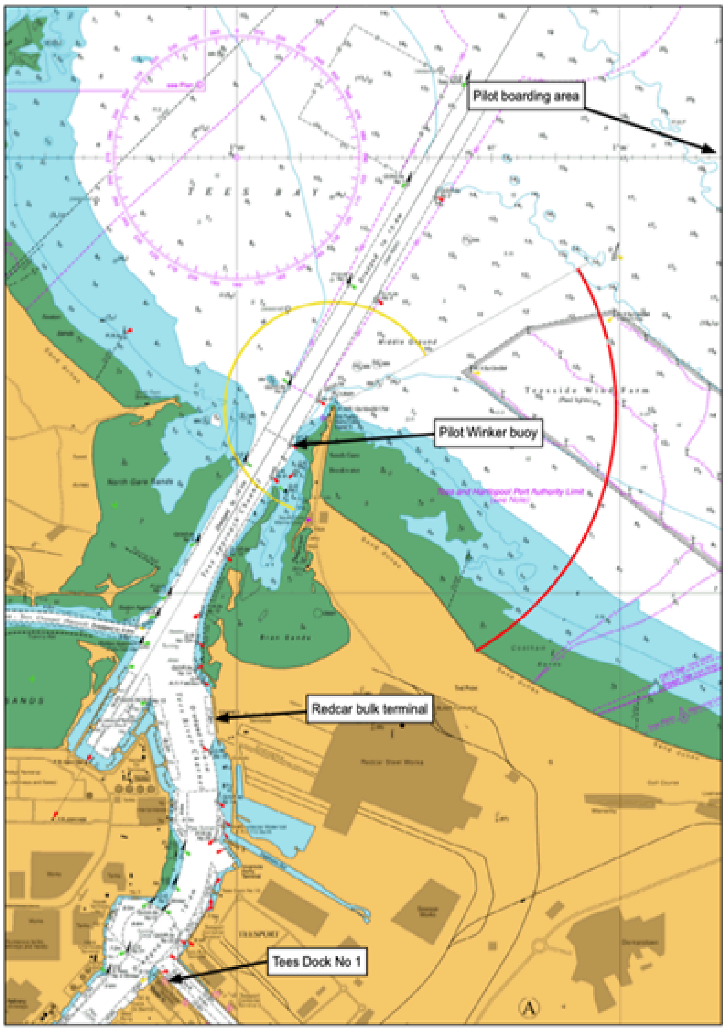
The accident analyzed in this study was based on the Marine Accident Investigation Branch (MAIB) report entitled "Collision between the bulk carrier Gülnak and the moored bulk carrier Cape Mathilde in the River Tees, England." This report provides the foundational data used in the analysis, offering detailed insights into the incident's circumstances and contributing factors as documented by MAIB (MAIB, 2020).

On April 18, 2019, a Turkey-registered bulk carrier "Gülnak" collided with a Panama-registered bulk carrier "Cape Mathilde" in the River Tees, England. The collision occurred as Cape Mathilde was moored alongside the "Redcar Bulk Terminal", and Gülnak was maneuvering along the main navigation channel under the guidance of a harbor pilot.

To provide the spatial context, Figure 2 shows an extract from chart BA2566, indicating the key locations relevant to the collision, including the navigation channel and mooring area. Despite the efforts of the bridge team to control the vessel's direction during a planned turn to port, the turn could not be sufficiently arrested, leading to the collision. Fortunately, the accident did not result in any injuries or environmental pollution; however, both vessels sustained significant structural damage, necessitating repairs.

Figure 2

BA2566 Chart Excerpt Highlighting Critical Locations



Source: MAIB, 2020

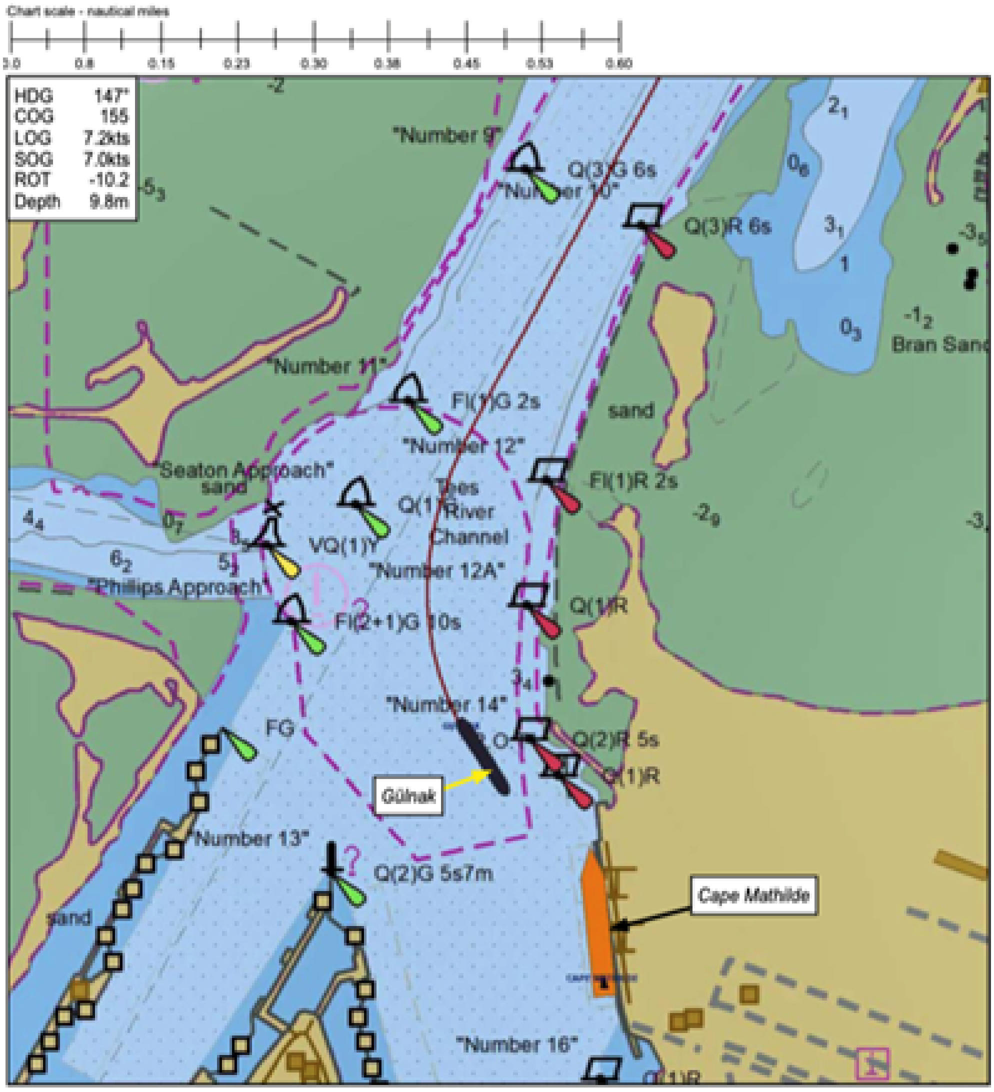
The incident began when Gülnak's pilot initiated a port turn intended to align the vessel with the main channel. As the turn progressed, control of the vessel's heading was lost despite the application of full starboard rudder and eventually full astern power. The turn rate was not adequately reduced, and the ship continued its trajectory toward Cape Mathilde.

Environmental conditions such as tidal flows and limited water depth further amplified the squat effect, reducing the vessel's maneuverability. The fully loaded condition of the vessel also constrained its ability to respond swiftly to navigational inputs, illustrating the compound challenges encountered during maneuvering.

The final moments before impact included attempts by the harbor pilot and master to arrest the turn by using additional maneuvers and increasing engine speed; however, these measures were insufficient. Figure 3 illustrates the positions of both vessels at 03:23:23, shortly before the collision, with Gülnak's engine set to "full astern" in a final attempt to slow down. At approximately 03:24 UT, Gülnak's port bow made contact with Cape Mathilde at an angle of 29°, traveling at a speed of 6.7 knots.

Figure 3

Vessel Positions at 03:23:23

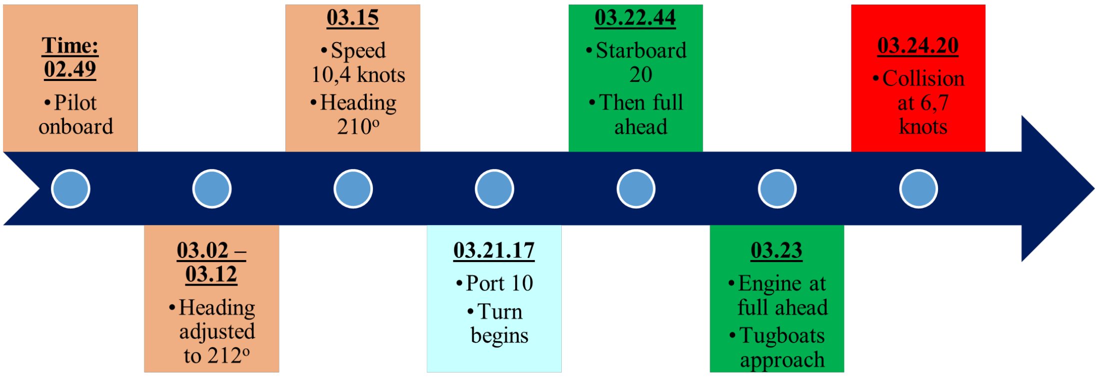


Source: MAIB, 2020

The sequence of critical events leading up to the collision between Gülnak and Cape Mathilde is summarized in Figure 4 , which illustrates the key interactions and decisions that contributed to the incident.

Figure 4

Timelines of Key Events in the Gülnak and Cape Mathilde Collision.



The MAIB report highlights multiple potential contributing factors although it does not identify a single root cause. Key factors considered included the bridge team's actions, the vessel's maneuverability under loaded conditions, possible hydrodynamic effects, and technical malfunctions; however, due to a lack of recorded rudder angle and engine speed data, these factors remain speculative. Additionally, a noted issue with Gülnak's main engine speed indicator, which was behaving erratically following the collision, added to the uncertainty of whether technical faults played a role in the loss of control.

In the wake of the incident, Teesport harbor authorities implemented measures to mitigate similar future occurrences, including enhanced guidelines for pilots regarding tidal flows, increased dredging operations and reinforcement of tugboat positioning procedures. Furthermore, Gülnak's owner, Gülnak Shipping Transport & Trading Inc., was advised to validate the vessel's handling characteristics and ensure the operational reliability of all bridge equipment.

This incident, which is characterized by a complex interplay of human, technical, and environmental factors, serves as an illustrative case for applying the Functional Resonance Analysis Method (FRAM) to uncover how systemic variability and functional interactions contributed to the eventual collision. In the subsequent sections, this case study is analyzed using FRAM to explore how the variability in key functions and their interactions may have amplified risk, ultimately leading to the accident.

FRAM-Based Accident Analysis

FRAM provides a structured framework for analyzing the Gülnak–Cape Mathilde collision by emphasizing the complex interplay of functions contributing to the accident (Hollnagel, 2013). Unlike conventional accident analysis methods, FRAM focuses on how functional variabilities within a system can resonate and create risk.

In this analysis, 15 distinct functions relevant to the incident were identified, and each function was described using the six FRAM aspects—Input, Output, Precondition, Resource, Control, and Time. These functions were selected to represent critical components of maritime operation and their interdependencies within the system, providing a detailed map of how variabilities in one function could propagate through others, ultimately contributing to the accident.

Table 1 provides an overview of these functions, including their type, time, and precision, to establish their relevance within the operational framework. Building on this foundation, Table 2 presents a detailed description of each function's six aspects. This structured description ensures consistency and clarity in the understanding of how each function operates and interacts. To enable accurate modeling, consistent terminology was applied across interconnected aspects, emphasizing the systemic nature of the accident and the propagation of variability within the system.

Table 1

Overview of Functions: Type, Time, and Precision Variability

Functions	Function Type		Time Variability		Precision Variability	
	Type	Reasoning	Time	Reasoning	Precision	Reasoning
F1: Pilot's Initial Maneuvering Commands	Human	This function involves real-time decision-making and physical inputs by the pilot, which are human-dependent.	On time: should be typical	The pilot's commands should ideally be timely to effectively control vessel maneuvering.	Acceptable: Typical	Note that precision is important; however, slight variability in the precision of commands is likely acceptable given human factors.
F2: Third Officer's Execution of Commands	Human	This function relies on the Third Officer's physical response to execute commands accurately.	On time: should be typical	Timely execution is crucial for maintaining maneuvering accuracy.	Acceptable: Typical	The human response is typically within acceptable limits, but minor imprecisity is expected.
F3: Speed Indicator Functionality	Technological	This function depends on the speed indicator.	On time: Normal, expected	Speed indicators should provide real-time feedback; delays are unlikely unless there's a system issue.	Precise: Normal expected	Technological equipment like a speed indicator typically provides precise data.
F4: Rudder Control Response	Technological	The rudder response is an equipment-based function controlled by the bridge team's input.	On time: Normal, expected	The operator should respond promptly to ensure vessel control.	Precise: Normal expected	The precision of the rudder angle adjustments.
F5: Environmental conditions: Water depth and currents	Organizational	Monitoring environmental conditions is based on organizational guidelines and external data.	On time: Likely	Environmental data should be timely, but minor delays may occur due to observational variability.	Acceptable: Possible	Environmental data only need to be reasonably precise to realize effective navigational awareness.
F6: Squat Effect on the Vessel	Technological	The squat effect is a physical response influenced by vessel design and operational speed.	On time: Normal, expected	The squat effect will occur predictably with changes in speed; thus, the timing is naturally aligned.	Acceptable: Unlikely	Slight variations in squat precision do not critically affect immediate maneuvering decisions.
F7: Communication with Tugboats	Human	Communication with tugboats requires human judgment and coordination.	On time: should be typical	Timely communication is necessary for effective assistance.	Acceptable: Typical	Communication precision is typically acceptable; minor inaccuracies can be managed.
F8: Tugboat Positioning and Readiness	Organizational	Operational planning manages tugboat positioning and readiness.	On time: Likely	Tugs should be in position on time; delays could affect maneuvering support.	Acceptable: Possible	Acceptable precision in the positioning of tugboats provides effective assistance.
F9: Pilot Adjustment to Vessel Speed	Human	The pilot's speed adjustments are based on real-time assessments.	On time: should be typical	Speed adjustments should be made in a timely manner to ensure effective control.	Acceptable: Typical	The precision of speed adjustment is generally within acceptable bounds.
F10: Bridge Equipment Readiness Check	Organizational	The readiness of equipment is an organizational procedure.	On time: Likely	Checks must be completed before departure to avoid delays.	Acceptable: Possible	Precision in readiness checks is acceptable; minor inaccuracies do not significantly affect safety.
F11: Monitoring of Vessel Position and Drift	Technological	Monitoring involves GPS and other navigation technologies.	On time: Normal, expected	Continuous real-time monitoring is expected for effective control.	Precise: Normal expected	High precision is expected from navigation systems to maintain the planned route.
F12: VDR (Voyage Data Recorder) Data Accuracy	Technological	VDR is a technological function that is responsible for data recording.	On time: Normal, expected	Data should be recorded in real time for post-incident review.	Precise: Normal expected	Accurate data are essential for post-incident analysis.
F13: Harbor Control Coordination	Organizational	Harbor coordination is managed through organizational protocols.	On time: Likely	Timely coordination is critical for maintaining traffic flow and safety.	Acceptable: Possible	Coordination precision is usually acceptable, with slight variability tolerable.

Functions	Function Type		Time Variability		Precision Variability	
	Type	Reasoning	Time	Reasoning	Precision	Reasoning
F14: Pilot's Communication with Harbor Control	Human	Communication is dependent on the pilot's interaction with the harbor control.	On time: should be typical	Timely communication is expected to ensure safe maneuvering.	Acceptable: Typical	In general, communication precision is acceptable for safe operations.
F15: Detection of Environmental Hazards (e.g., Shallow Areas)	Technological	The detection is based on radar and other monitoring technologies.	On time: Normal, expected	Real-time hazard detection is essential for immediate response.	Acceptable: Unlikely	Precision in hazard detection is ideal but not critical in cases in which observation can be confirmed.

Table 2

Functional Aspects of Functions

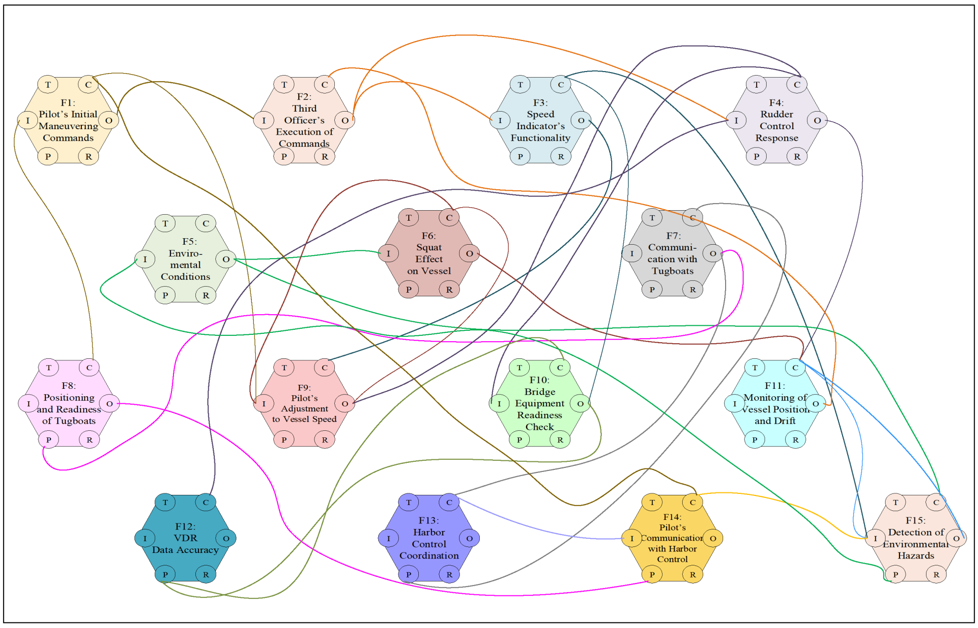
Functions	Functional Aspects					
	Input	Output	Requirement	Resource	Control	Time
F1: Pilot's Initial Maneuvering Commands	Tugboat position as input for initial maneuvering.	Pilot maneuvering commands for heading and speed adjustment. Command directives for speed adjustment.	Tugboat readiness enables pilot communication.	Maneuvering commands requiring bridge team response.	Command directives for speed adjustment. Pilot communication with harbor control supporting maneuvering.	Timing command issuance is critical for course alignment.
F2: Third Officer's Execution of Commands	Pilot maneuvering commands for heading and speed adjustment.	Third Officer's execution of heading and speed adjustments. Command implementation for rudder adjustment.	Accurate input from the pilot for command execution.	Rudder and engine settings for course adjustments.	Position monitoring is used as command execution control.	Execution timing is critical for immediate course correction
F3: Speed Indicator Functionality	Third Officer's execution of heading and speed adjustments.	Speed indicator for accurate adjustments.	Equipment readiness supporting speed indicator accuracy.	Real-time speed feedback for situational awareness.	Speed data support for hazard detection. Equipment readiness supporting speed indicator accuracy.	Continuous speed monitoring to support adjustments.
F4: Rudder Control Response	Command implementation for rudder adjustment. VDR data for rudder control validation.	Rudder response affects vessel position and drift.	Verified VDR data for accurate rudder control.	Rudder systems are responsive to command adjustments.	Verification of bridge equipment readiness. Speed adjustment for rudder control response.	Timely rudder response for navigation adjustments.
F5: Environmental conditions: Water depth and currents	Awareness of environmental conditions.	Environmental conditions influencing squat effect. Environmental data for hazard detection.	Continuous monitoring of real-time environmental input.	Real-time environmental data for situational awareness.	Environmental factors affecting vessel dynamics.	Immediate data needed during high-risk navigation.
F6: Squat Effect on the Vessel	Environmental conditions influencing squat effect.	The squat effect influences vessel position and drift.	Environmental awareness to anticipate squat impact.	Squat data for speed and rudder adjustments.	Squat effect as input for speed adjustment. Speed changes influence the squat effect.	Timely squat data to support navigation choices.

Functions	Functional Aspects					
	Input	Output	Requirement	Resource	Control	Time
F7: Communication with Tugboats		Tugboat communication ensures readiness. Communication for harbor control coordination.	Established protocol for tugboat readiness.	Communication channels with tugboats.	Communication for the coordination of tugboat actions.	Timely communication to secure tugboat support.
F8: Tugboat Positioning and Readiness	Tugboat communication ensures readiness.	Tugboat readiness enables pilot communication with harbor control.	Tugboat communication ensures readiness. Clear positioning for immediate tugboat response.	Tugboat availability for maneuvering support.	Tugboat position as input for initial maneuvering.	Tugboat readiness timing is critical for effective support.
F9: Pilot Adjustment to Vessel Speed	Command directives for speed adjustment. Squat effect as input for speed adjustment.	Speed adjustment for rudder control response. Speed changes influence the squat effect.	Accurate speed data for adjustments.	Engine power adjustments for speed control.	Speed indicator for accurate adjustments.	Timely adjustments to manage vessel speed.
F10: Bridge Equipment Readiness Check	Verification of bridge equipment readiness.	Equipment readiness supporting speed indicator accuracy. Verified bridge equipment for reliable data.	Functional check before departure.	Operational bridge equipment.	VDR accuracy depends on equipment readiness.	Pre-departure timing for equipment checks.
F11: Monitoring of Vessel Position and Drift	Position data for environmental hazard detection.	Position monitoring is used as command execution control.	Reliable data for position and drift monitoring.	Real-time monitoring systems.	Rudder response affects vessel position and drift. The squat effect influences vessel position and drift. Position data for environmental hazard detection. Hazard detection control and drift monitoring.	Continuous monitoring is required during navigation.
F12: VDR (Voyage Data Recorder) Data Accuracy	Equipment accuracy as requirement for VDR data accuracy.		Verified bridge equipment for reliable data. VDR accuracy depends on equipment readiness.	Data recording systems.	VDR data for rudder control validation.	Continuous recording for post-incident review.
F13: Harbor Control Coordination	Harbor control as input for pilot communication.	Harbor control coordination required for tugboat communication.	Communication for the coordination of tugboat actions. Established protocols with harbor control.	The harbor control contact systems.	Communication for harbor control coordination. Harbor control as input for pilot communication.	Timely coordination is critical during the approach.
F14: Pilot's Communication with Harbor Control	Harbor control as input for pilot communication.	Pilot communication with harbor control supporting maneuvering.	Tugboat readiness enables pilot communication with harbor control.	Communication systems with harbor control.	Harbor communication as input for hazard detection.	Communication timing during maneuvering.

Functions	Functional Aspects					
	Input	Output	Requirement	Resource	Control	Time
F15: Detection of Environmental Hazards (e.g., Shallow Areas)	Speed data support for hazard detection. Position data for environmental hazard detection. Harbor communication as input for hazard detection.	Hazard detection control and drift monitoring.	Awareness of environmental conditions.	Sensors and monitoring tools.	Environmental data for hazard detection.	Continuous hazard detection for safe navigation.

Figure 5

Vessel Positions at 03:23:23



Source: MAIB, 2020

Extending the scope of this analysis, Table 3 provides a comprehensive representation of the functional interactions identified during FRAM modeling. This table highlights which aspects of each function (e.g., Input, Output, Control) are interconnected, emphasizing the critical pathways through which variabilities propagate within the system. This level of detail provides a foundational understanding of the emergence of systemic risks during the event.

Table 3

Functional Interactions

Function	Connection	Expression
F1	Output (F1) → Input (F2)	Pilot maneuvering commands for heading and speed adjustment.
	Control (F1) → Input (F9)	Command directives for speed adjustment.
F2	Output (F2) → Input (F3)	Execution of speed adjustments for accurate indicator readings.
	Output (F2) → Input (F4)	Command application for rudder response.
F3	Output (F3) → Control (F9)	Speed feedback for pilot adjustments.
	Control (F3) → Input (F15)	Speed data supporting hazard detection.
F4	Output (F4) → Control (F11)	Rudder response influences position and drift monitoring.

Function	Connection	Expression
F5	Control (F4) → Input (F10)	Rudder control input for bridge readiness verification.
	Output (F5) → Input (F6)	Environmental factors impacting squat.
	Output (F5) → Control (F15)	Environmental data for hazard detection.
F6	Output (F6) → Control (F11)	Squat influences position and drift monitoring.
	Control (F6) → Input (F9)	The squat impact is considered in the speed adjustment.
F7	Output (F7) → requirement (F8)	Coordination ensures tug readiness.
	Output (F7) → Control (F13)	Communication point for harbor control coordination.
F8	Output (F8) → requirement (F14)	Tugboat readiness enabling harbor communication.
	Control (F8) → Input (F1)	Tug position as input for pilot's initial maneuvers.
F9	Output (F9) → Control (F4)	Speed adjustments affect the rudder response.
	Output (F9) → Control (F6)	Speed impact as a control factor for squat.
F10	Output (F10) → Control (F3)	Readiness check supporting speed indicator accuracy.
	Output (F10) → requirement (F12)	Equipment readiness ensuring VDR accuracy.
F11	Output (F11) → Control (F2)	Position monitoring is a factor in 3/O's command execution.
	Control (F11) → Input (F15)	Position and drift data are inputs for hazard detection.
F12	Requirement (F12) → Control (F10)	VDR accuracy depends on equipment functionality.
	Control (F12) → Input (F4)	The VDR data ensure the rudder response accuracy.
F13	Requirement (F13) → Control (F7)	The harbor control coordination enables tug communication.
	Control (F13) → Input (F14)	Harbor control as input for pilot communication.
F14	Output (F14) → Control (F1)	Harbor communication supporting maneuver commands.
	Control (F14) → Input (F15)	Harbor control communication for hazard detection.
F15	Requirement (F15) → Input (F5)	Environmental conditions influence hazard detection.
	Output (F15) → Control (F11)	Detected hazards impacting position monitoring.

These interactions are visualized in Figure 2, which was developed using the FMV model to present the FRAM model of functional interactions and their variabilities. By combining the data presented in Table 3 with the visual representation in Figure 2, the analysis provides a multidimensional view of how the collision unfolded due to cascading variability. Building on the FRAM analysis, the critical moments leading to the collision were examined, with a focus on how timing issues, equipment limitations, and communication delays dynamically interacted to compound the risk. The analysis identified key moments at which the variabilities in function alignment escalated into systemic risks, as detailed below:

- Initial Maneuvering Commands (03:02–03:12): Variabilities in the pilot's incremental adjustments (F1) propagated to the Third Officer's execution of commands (F2), leading to minor misalignments. These misalignments were not corrected in subsequent functions, which gradually reduced system stability.
- Escalation of the Turn Rate (03:21:17): Timing delays in the rudder response (F4) and speed adjustments (F9) intensified an unexpected increase in the vessel's turn rate. This created a resonance effect that amplified misalignment and led to an unsustainable turn angle.
- Speed Adjustment and Squat Effect (03:22:44): The "full ahead" command (F9) aimed to stabilize the vessel but amplified the squat effect (F6), reducing rudder efficacy. Variabilities in environmental factors such as water depth (F5) compounded this effect.
- Communication and Tugboat Coordination (03:23): Delays in communication and positioning hindered attempts to engage tugboat support (F7, F8), resulting in a missed opportunity for external assistance.

This missed opportunity for external intervention reduced the system's ability to recover from accumulated risks.

- Final Rudder Adjustments and Drift Monitoring (03:23–03:24): Cumulative delays and misalignments in rudder control (F4) and drift monitoring (F11) confirmed the inevitability of the collision.

Finally, Table 4 summarizes the function interactions, showing how the variabilities led to resonance effects and increased systemic risks during the incident.

Table 4

Functional Interactions

Function Interaction	Interaction Description	Resonance Effect	Increased Risk
F1: Pilot's Initial Maneuvering Commands → F2: Third Officer's Execution of Commands	Accurate timing between pilot commands and third officer execution is essential for safe maneuvering.	Misalignment in response timing leads to potential resonance, which affects maneuver precision.	Untimely maneuvers increase the turn rate, thus elevating the collision risk.
F2: Third Officer's Execution of Commands → F4: Rudder Control Response	The timely execution of rudder adjustments affects vessel control, especially in critical turns.	Delays create resonance in the rudder control, which reduces maneuverability.	A slow rudder response can cause unexpected deviations, increasing the susceptibility of the engine to environmental factors.
F3: Speed Indicator's Functionality → F9: Pilot Adjustment to Vessel Speed	Accurate speed data are crucial for the pilot's control decisions.	Erroneous speed readings create resonance in speed adjustments, which affects maneuver judgment.	Misjudged speed reduces maneuverability, increasing collision risk in restricted waters.
F4: Rudder Control Response → F11: Monitoring of Vessel Position and Drift	Effective rudder control helps maintain positional accuracy.	Delays in the rudder response resonate during drift monitoring, thereby complicating navigation.	Positional drift increases difficulty in course control, heightening collision risk.
F5: Environmental Conditions → F6: Squat Effect on the Vessel	Water depth and currents amplify squat effects, thereby affecting vessel stability.	Shallow waters or high currents resonate with the squat, reducing the rudder efficacy.	The amplified squat effect decreased maneuverability, thereby increasing the collision risk in narrow channels.
F7: Communication with Tugboats → F8: Tugboat Positioning and Readiness	Effective communication with the tugboats ensures timely intervention.	Miscommunication delays the tug positioning, creating resonance that limits the support.	Delayed tug support increases the collision risk by reducing the available maneuvering assistance.
F8: Positioning and Readiness of Tugboats → F1: Pilot's Initial Maneuvering Commands	Tug readiness affects the pilot's maneuvering strategy.	Poor tug positioning influences the pilot's commands, creating resonant effects in maneuvering adjustments.	Inadequate tugboat support during maneuvering increases the control challenges and collision potential.
F10: Bridge Equipment Readiness Check → F12: VDR Data Accuracy	Verifying the bridge equipment functionality ensures accurate VDR recordings.	Equipment malfunctions resonate within the VDR data, impacting the post-accident analysis.	Inaccurate VDR records hinder event reconstruction, thereby limiting the understanding of causative factors.
F11: Monitoring of Vessel Position and Drift → F2: Third Officer's Execution of Commands	Continuous position monitoring informs Third Officer's actions for timely adjustments.	Delays in monitoring resonate during command execution, reducing response precision.	Lagged responses increase the drift, reducing the vessel control and increasing the collision likelihood.
F13: Harbor Control Coordination → F14: Pilot's Communication with Harbor Control	Coordinated communication with the harbor control system supports real-time navigation alignment.	Delayed communication with harbor control resonates in the pilot's situational awareness, which affects maneuver decisions.	Untimely updates complicate navigation and elevate the risk in restricted maneuvering areas.

By analyzing these interactions, this study identified how variabilities in timing, precision, and response across multiple functions interacted to generate risks. This highlights the systemic nature of risk and the contribution of dependencies and external conditions to the collision.

Through the FMV's functionality, this analysis emphasizes the importance of addressing variability at multiple levels, including the function itself, upstream influences, and external conditions. Such insights are critical for improving maritime operations' resilience under complex and high-risk scenarios.

Findings and Discussions

This section explores the complex interplay of human, environmental, and technical factors contributing to loss control in maritime operations, as revealed through the analysis of the Gülnak–Cape Mathilde collision. By integrating the insights from the FRAM-based assessment with broader maritime safety perspectives, the findings provide a comprehensive understanding of how systemic variabilities interact dynamically under high-stress conditions. These findings are structured under four key themes: human factors and decision-making under stress, environmental conditions and their dynamic impacts, uncertainty and equipment reliability, and preventive recommendations with their potential effects.

Factors and Decision-Making Under Stress

Human factors and decision-making under stress play a pivotal role in maritime safety, as variability in human performance can propagate through interconnected functions, amplifying risks (Ay et al., 2024). The FRAM analysis highlighted how variability in the pilot's commands (F1) and the Third Officer's execution of those commands (F2) contributed to misalignments during critical moments. For instance, delays in the pilot's commands influenced the timing and precision of the Third Officer's responses, creating a cascading effect on downstream functions such as F4 (Rudder Control Response). These misalignments were particularly critical during high-pressure moments, such as the escalation of turn rate.

The early morning timing of the incident (around 03:00) likely intensified these human performance variations. Circadian lows during this period are known to impair cognitive function, reducing alertness and reaction times (Jepsen et al., 2017; Maternová et al., 2023). In this case, the pilot's reactive command escalation—from "port 10°" to "hard-to-starboard"—illustrates decision-making under stress, where high-pressure situations can compromise judgment and lead to suboptimal outcomes (Brooks and Greenberg, 2022; Oraith et al., 2021).

Another critical factor was communication lapse. Variability in F1 and F7 (Communication with Tugboats) introduced delays and inconsistencies, hindering effective coordination between the bridge team and external support. These communication challenges propagated to F8 (Tugboat Positioning and Readiness), reducing the tugboats' ability to assist during critical moments. Studies have consistently emphasized the importance of timely and clear communication in maritime operations to prevent cascading errors (Argüelles et al., 2021; Wahl and Kongsvik, 2018).

Fatigue also likely played a role in amplifying these variabilities. Although specific data on crew fatigue during the incident are unavailable, the timing of the event aligns with circadian rhythm lows, where human performance is typically diminished (Jepsen et al., 2017; Maternová et al., 2023). The FRAM analysis indicates that the fatigue-induced variability in F1 and F2 contributed to slower reaction times and increased the likelihood of errors in high-stake decision-making scenarios.

These findings underscore the need for targeted interventions to address human variability. Training programs that focus on stress management and resilience can help crew members maintain their cognitive performance during high-pressure situations. In addition, standardizing communication protocols and enhancing coordination mechanisms between functions such as F1 and F7 are essential to minimize the cascading effects of variability. By integrating these measures, maritime operations can enhance decision making and overall system stability.

Environmental Conditions and Dynamic Impacts

Environmental factors such as water depth, currents, and the squat effect significantly influence a vessel's maneuverability. The FRAM analysis of F5 (Environmental Conditions) and F6 (Squat Effect) revealed how these factors interacted dynamically, worsening the risks during the collision. Specifically, the pilot's decision to increase speed (F9) in response to the escalating turn rate amplified the squat effect, reducing rudder efficacy and under-keel clearance. This finding aligns with documented hydrodynamic challenges in confined channels, where squat effects are more pronounced (Tezdogan et al., 2016; Maljković et al., 2024).

The analysis highlighted how environmental variability introduced additional uncertainties. For instance, the channel's narrowness and sudden changes in water depth compounded the vessel's maneuverability problems. These variabilities interacted with human decisions, such as the pilot's reactive speed adjustments, creating a cascading effect throughout the system.

Beyond these specific findings, predictive methods and modeling tools have been emphasized in the literature for their potential to mitigate environmental risks. By integrating tools that anticipate hydrodynamic impacts, bridge teams can make more informed decisions under challenging conditions (Yang and el Moctar, 2024). The FRAM model underscores the importance of such tools in capturing and addressing environmental variabilities that pose significant risks to maritime safety.

Uncertainty and Equipment Reliability

Technical equipment reliability is a cornerstone of maritime safety, as even minor malfunctions can cause significant uncertainties. The FRAM analysis identified critical variabilities in functions such as F3 (Speed Indicator) and F4 (Rudder Control Response), demonstrating how these technical failures propagated through the system. For example, the malfunctioning speed indicator provided inaccurate data, which impaired the pilot's ability to make informed decisions. Similarly, delays in the rudder control response reduced the vessel's ability to recover from deviations, amplifying the risks during critical maneuvers.

These findings align with broader concerns about the reliability of onboard systems in high-stake operations. Predictive maintenance strategies, such as those incorporating Bayesian fault detection, have been shown to enhance equipment reliability and reduce uncertainty (Daya and Lazakis, 2024; Rigas et al., 2024). The integration of advanced diagnostic tools into routine operations can provide early warning of potential failures, thereby allowing timely interventions.

The FRAM model also highlighted how equipment-related variabilities interacted with human and environmental factors, emphasizing the need for a holistic approach to managing uncertainty in maritime operations. By addressing these interdependencies, maritime stakeholders can better mitigate risks and enhance operational resilience (Simion et al., 2024; Bicen and Celik, 2023).

Preventive Recommendations and Their Potential Effects

Building on the insights gained from FRAM analysis, this section outlines preventive strategies designed to address the identified variabilities. For example, real-time feedback systems targeting F9 (Speed Adjustments) and F4 (Rudder Control Response) were identified as critical for improving situational awareness and enabling timely corrective actions. Such systems can provide pilots with immediate feedback on vessel responses under various conditions, thus reducing the likelihood of misaligned maneuvers (Aylward et al., 2022).

Furthermore, enhancing the tugboat coordination, as analyzed in F7 and F8, can provide essential external support during emergencies. The proactive positioning of tugboats and standardized communication protocols can mitigate timing delays and improve response readiness (Paulauskas et al., 2021). Scenario-based training simulations, which replicate high-pressure scenarios, are also emphasized as essential for building stress resilience and enhancing decision-making skills among bridge teams (Dominguez-Péry et al., 2021).

Finally, advanced predictive algorithms for analyzing squat effects and lateral drift (Xiang et al., 2024), as well as upgraded Voyage Data Recorder (VDR) systems, can provide both real-time operational support and valuable data for post-incident analyses (Zhang et al., 2025). These enhancements align with the FRAM model's emphasis on capturing and managing functional variabilities to prevent risk escalation.

Conclusions and Future Directions

This study applied the Functional Resonance Analysis Method (FRAM) to analyze the Gülnak–Cape Mathilde collision, exploring incidents shaped by complex interactions and systemic uncertainties. The FRAM approach effectively captured the detailed interactions and functional variabilities contributing to the accident, illustrating how minor variations can accumulate, leading to control loss in dynamic maritime environments. Unlike traditional linear models, FRAM's capacity to represent the interconnected nature of maritime functions over time highlights its suitability for complex accident analysis, particularly when the causation is ambiguous.

Structuring the FRAM application in an uncertain environment, this study demonstrates a novel approach to understanding accidents where identifying specific causes is challenging, and interactions among multiple functions lead to increasing risks. This perspective demonstrates that FRAM is an adaptable and resilient tool for capturing systemic variabilities that may remain undetected by conventional methods. Such a framework has valuable potential for advancing future accident investigations and enhancing safety management strategies in the maritime domain.

While the proposed framework offers valuable insights, certain limitations should be considered. The qualitative nature of FRAM may constrain its predictive capacity, especially in quantifying risk probabilities, which can be addressed by integrating it with quantitative models. In addition, FRAM's reliance on detailed incident data poses a challenge because maritime accident reports may not always provide the comprehensive documentation necessary for a full analysis. The proposed method also assumes a level of consistency in the functional data, which may not always be realistic in dynamic maritime operations. Variations in the availability and reliability of data—such as incomplete voyage data recorder (VDR) records or limited details on human decision-making processes—can introduce uncertainty into the analysis. Furthermore, the lack of standardized procedures for applying FRAM across different contexts may result in inconsistent outcomes; thus, methodological guidelines should be refined to broaden applicability. Future studies should adopt mixed-method approaches that enhance both the depth and precision of FRAM-based investigations.

Moving forward, future research could build on these findings by incorporating quantitative risk models, such as Bayesian Networks, to introduce probabilistic elements into FRAM analysis, offering a more nuanced understanding of risk accumulation and intervention points. In addition, applying FRAM to a broader dataset of maritime incidents would enhance its generalizability across different types of accident and operational scales. Further advancements in FRAM visualization tools can also support real-time functional analysis, enabling maritime professionals to anticipate and manage variability before it escalates into critical issues. Integrating these tools into bridge operations and training could improve situational awareness and preemptive risk management, ultimately contributing to safer and more resilient maritime practices.

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