A Study of Safe Ship Navigation Using Functional Resonance Analysis Method forAssessing System Resilience Potency

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A Study of Safe Ship Navigation Using Functional Resonance Analysis Method for Assessing System Resilience Potency

(システムレジリエンス力の評価のための機能共鳴分析手法に基づく船舶の安全航行に関する研究)

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Summary

This dissertation explores the development of safety assessment in ship navigation from the perspective of resilience engineering. It includes a proposed method and a demonstration of the usability of Safety-II in the maritime field. We emphasize the significance of learning from successful maneuvering and how such insights can contribute to improving safe ship navigation.

The traditional safety assessment, based on analyzing and identifying accidents to create a safer system, undoubtedly has a significant contribution to our industrial development. In the maritime industry, e.g., the MV Herald of Free Enterprise is one of the most remarkable accidents that had a major impact on changing ship safety management. This traditional safety approach involves decomposing the system into smaller components, with safety understood as these components working with no deviation. This implies that each component is assumed to work bimodally, either functioning correctly or malfunctioning. Through accident investigations, preventing potential component malfunctions is considered a solution to protect the system from failure.

However, in the real world, such situations are not always the case. Technical components, indeed, manifest bimodal functionality, unlike humans and organizations. Most of today's systems are a combination of these social and technical components, known as socio-technical systems. They are complex with a lot of uncertainty, making them practically hard to decompose and specify. Humans, whether as individuals or groups, have variable capacities that enable them to adapt their performance to working conditions. In this scenario, disturbances, such as those from the natural environment or malfunctions in technical components, can be adjusted so that the system can still achieve its desired goals. Consequently, system performance must vary (adjustable and flexible) to meet the demands of everyday work.

In resilience engineering paradigm, this working adjustment is understood as the reason why the system can successfully achieve the desired goal most of the time but occasionally, in exceedingly rare events, fails. As the source of both successful operations and failures is this approximate adjustment, it is considered essential to understand safe operations not only from incidents or accidents but also from where safety actually exists, which is in successful events. Thus, through this dissertation, we have attempted to elaborate on this idea and how to utilize it for better ship navigation.

This dissertation has 6 chapters and its organized as explained below.

Chapter 1 – Introduction: this chapter contained research's general background, motivation, limitation and aims. The general idea was explained briefly, in specific, introduce the resilience engineering point of view and the potential implementation to support the development of safety in maritime industry.

Chapter 2 – Literature Review: this chapter explored the fundamental basis of literature for the application of resilience engineering in maritime domain. It explains the concept of proposed method used in this dissertation, including the Functional Resonance Analysis Method (FRAM), Environmental Stress (ES) Model, and Dynamic Bayesian Network (DBN). Moreover, the method implementation, as well as the framework and development for safe ship navigation analysis is also presented in this chapter.

Chapter 3 – Field observation (Direct onboard observation of Fukae-maru): this chapter established a foundational understanding of the practical onboard activities involved in ship navigation. The development of a conceptual functional model for the everyday operations of a ship was initiated with field observations onboard Fukae-maru, a training ship owned by Kobe University. The chapter introduced the dynamic FRAM model specifically designed for maneuvering activities. It represented a comprehensive exploration of the continuous processes inherent in the system, emphasizing the development of maneuvering strategies essential for overcoming obstacles encountered during voyages. Furthermore, the chapter elaborated on the system's resilience potency, including the abilities to monitor, learn, anticipate, and respond, all of which were integral components of the proposed functional model.

Chapter 4 – Assessing Ship Officer Flexibility in Challenging Ship-Ship Encounter: A Simulation Study: this chapter discussed a detailed exploration of FRAM analysis in the context of challenging ship-ship encounter situations. The aim was to gain a profound understanding of the flexible and adaptable capacity of ship officers to maintain normal system functioning under unexpected situations. The data for this analysis was generated through ship-handling simulation experiments. In addition to FRAM, the analysis was further enhanced by incorporating the Environmental Stress (ES) model. This combination brought attention to the potency of risk concepts and resilience engineering for complementing each other and enriching safety assessments. Consequently, the FRAM analysis, supported by the objective assessment from the ES model, provided a deeper understanding of different working adjustments made by participants. It shed light on the potential for system improvement and drew lessons from successful maneuvering decisions.

Chapter 5 – Extended Approach for Ship Officer Performance Based on FRAM-DBN Analysis: this chapter proposed a mathematical modeling approach to express performance variation in the form of the probability of changes in performance control modes. Furthermore, the analysis was also utilized to introduce a flexible iteration process for FRAM function performance variability. The temporal modeling was presented using Dynamic Bayesian Network, defining function characteristics in four control modes: strategic, tactical, opportunistic, and scrambled. The application of this method was demonstrated through a case study selected from one of the events captured in the ship handling simulation presented in Chapter 4. This initial application successfully illustrated performance changes over time, degraded performance through function coupling, and the expected performance adjustments to overcome unexpected situations.

Chapter 6 – Conclusions: this chapter concluded the findings of the studies proposed in this dissertation. It addresses the critical point of the need for the resilience engineering paradigm to enhance safety in shipping operations and its contribution to the existing literature.

The studies presented in this dissertation aim to underscore the importance of applying resilience engineering to enhance safety assessments in shipping operations. Despite the anticipated shift towards Maritime Autonomous Surface Ships (MASS) in the future, potential delays due to environmental crises or regionalized economic transitions remain possible. In any future scenario, complexity will always be a part of the system. Hence, the need for an adaptive and flexible system remains crucial. It implies the relevance of developing safety assessments based on resilience engineering for the maritime industry. Moreover, the current expansion of FRAM analysis provides separate solutions for Safety-I–Safety-II integration and mathematical simulation for performance variability. This needs improvement in the future to become a unified solution capable of offering both reactive and proactive measures while harnessing positive surprises for system performance enhancement. Such a unified solution can draw insights from both successful and failed events to comprehend system complexity.

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Chapter 1
Introduction

1.1 Research Background

The maritime industry stands as a cornerstone of global commerce and connectivity, serving as the lifeblood of international trade. Its vast network of ships, from merchant ships to fishing vessels, facilitates the movement of goods, fuels economies, and connects distant shores. The growth of this industry is evident in the increasing volume of global maritime transportation, which sees consistent annual expansion [1], [2]. This is directly proportional to the rising number of ships and shipping activities. However, with this surge in maritime endeavours, an inevitable consequence has been a rise in accidents. Statistical data from The Japan Transport Safety Board noted that 8109 marine accidents occurred during the period 2010–2019 [3]. Subsequently, safety remains an important issue in marine transportation.

The International Maritime Organisation (IMO) has recognized the profound link between the human element and safety in ship operations [5]. The initiative particularly considered regulations and guidelines that support personnel development within the ship domain. For-

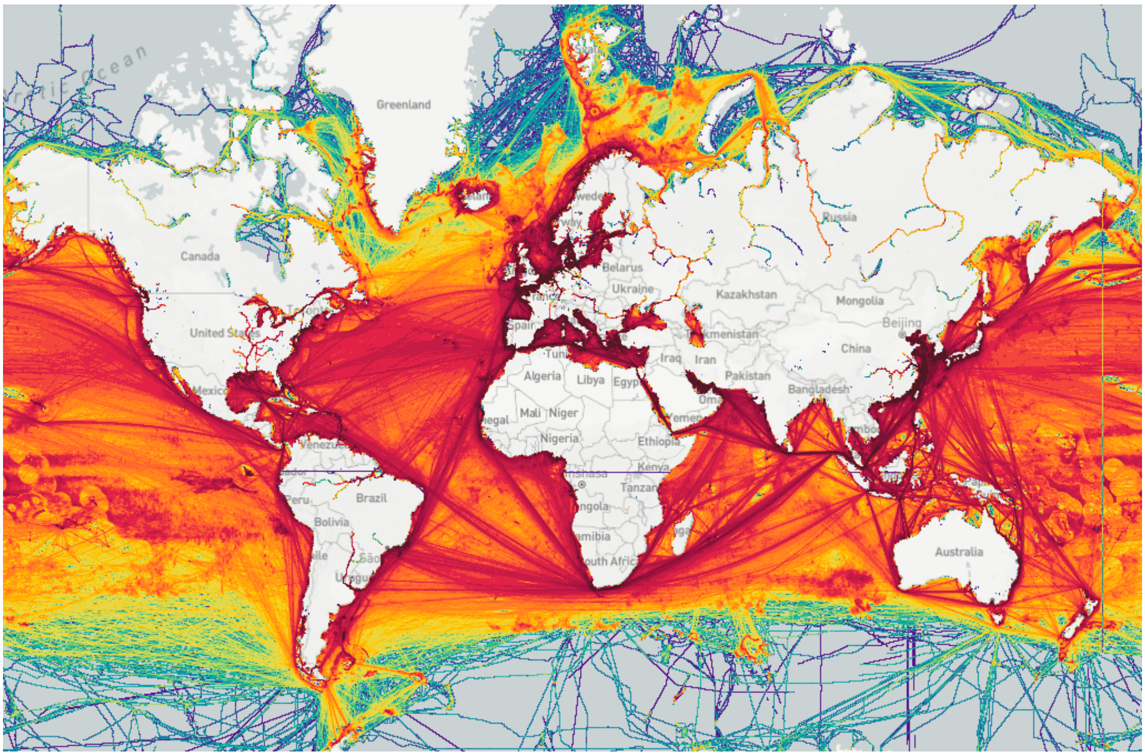

Figure 1.1. World shipping trade connection [4].

-example, the International Convention on Standards of Training, Certification, and Watchkeeping for Seafarers was the first IMO product to standardise the varied training, certification, and watchkeeping practices across individual countries [6]. Moreover, other commitments to enhance safety were made by establishing the safety-management regulation, that is, the International Safety Management (ISM) Code in 1993 [7]. This convention was strongly affected by the MV Herald of Free Enterprise accident and other severe ship accidents in the late 1980s [8].

Regulation alterations and system design changes are invariably responses to accidents. The Formal Safety Assessment (FSA) methodology introduced by IMO is an example of this reaction to the rule-making process for risk mitigation and safety improvement of maritime transportation [9]. Deeper applications can be incorporated with Human Reliability Analysis (HRA) to assess contributing factors related to human elements. For instance, a technique such as Human Factors Analysis and Classification System (HFACS) and Cognitive Reliability Error Analysis Method (CREAM) are methods that have been widely applied to assess human and organisational factors involved in maritime accidents [10]. Further elaboration has proposed a technique to systematically characterise the potential causation of seafarers' unsafe acts and their complex relationship [11]. Quantitative modeling, such as Bayesian Network analysis, has also made significant contributions to the analysis of maritime accidents in various instances [12]–[15]. This concerted effort to improve safety has notably benefited the maritime industry.

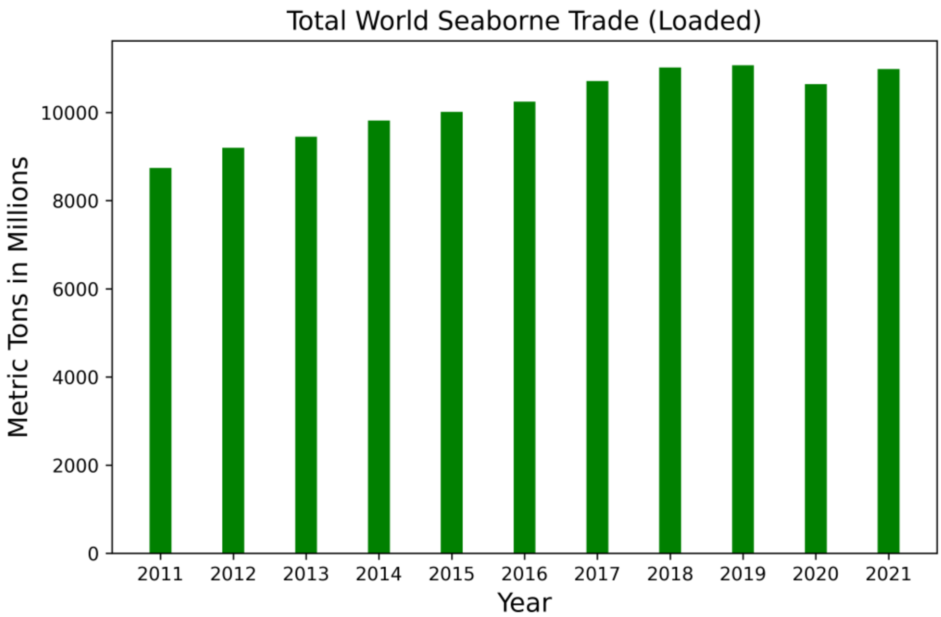

Figure 1.2. A data of total loaded cargo in the past decade [16].

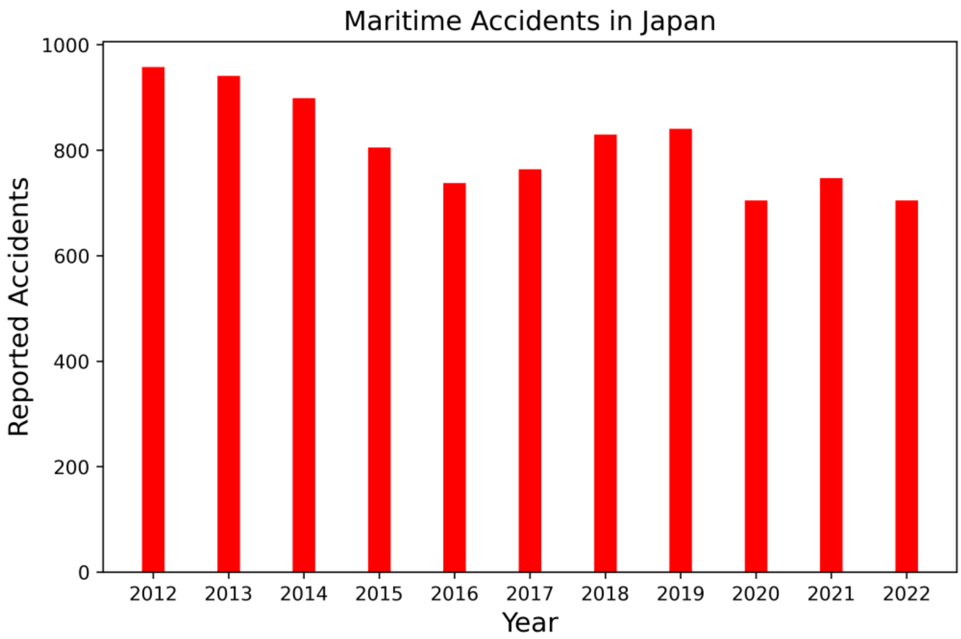

Figure 1.3. The Japan ship accident data in the past decade [3].

Nevertheless, some viewpoints from this perspective underline that the dynamic nature of human performance cannot be fully captured by HRA [17]. This stimulates discourse on the possibility of adopting a different perspective as a complementary solution. Resilience engineering (RE) offers a systemic framework by defining safety as an emergent phenomena that arises from complex socio-technical systems [18]. In their review of RE, Patriarca *et al.* [19] have confirmed the need for RE in safety analysis focusing on system functioning and work-as-done, defining the system performance in four cornerstones of resilience (monitor, learn, respond, and anticipate). In addition, further elaboration of this idea has generated new terminology in safety called Safety-II [20].

Human actions have been identified as contributing to 89.5% of accidents or contributing factors in marine casualties [21]. Although the exact origin of this widely held belief is challenging to trace [22], it has often been cited as one of the reasons for advocating autonomous ships as an alternative with potential benefits for future shipping operation [23]. However, the latest international maritime trade data recorded that more than ten billion tons of loaded cargo have been successfully transported [1]. It is undeniable that this successful operation was also achieved through human influence. It leads to the reasoning that successes and failures emerge from working adjustment and cannot be attributed to specific components, e.g., humans [24]. A former contribution related to this perspective done by Leveson [25] has addressed the need to go beyond this blame assignment and stresses the essence of understanding system functioning by control theory. Therefore, it is considered necessary to view human ability as a resource for emergency safety, not only as a source of the problem. This transformation promotes a more proactive safety practice [26], creating foresight to facilitate action before people get injured [27]. From the Safety-II perspective, this study seeks opportunities to learn how resilience manifests in actual ship operation.

1.2 Motivation

Safety remains an essential issue in today's industry. While technological advancements have significantly improved our system safety, they have also contributed to increasing system complexity. In the maritime domain, particularly in shipping operations, autonomous ships have gained immense popularity over the past decade. The motivation behind this trend is driven by a declining number of seafarers and safety concerns pointing to human error as the primary cause of accidents.

We should acknowledge that humans are the source of variability in the system. However, this does not mean that the undesired outcomes are rooted from this variable component. Our dynamic nature in operating these systems is an inherent part of the equation. This implies that work variability is necessary to adapt to the dynamic nature of system operations. Therefore, human error is viewed as outcomes rather than causes from this point of view. Most of the time, variability in performance adjustment resulting to the desired outcomes, but sometimes, in a very low frequency, it fails.

The motivation behind this dissertation stems from the need to enhance safety assessments from this new perspective. The future of shipping operations remains uncertain. While fully autonomous ships are a highly anticipated development, it is still unclear whether they will operate entirely without human intervention or collaborate with advanced technology in a mixed operational model. The certain situation is this transition will occur gradually, creating a hybrid operational environment where autonomous and traditional ships coexist. In this case, we believe the system must possess flexible ability to cope with this potential escalation of system complexity. Therefore, this research proposes a novel method for ship safety assessment based on the Functional Resonance Analysis Method (FRAM). Furthermore, an extended version of FRAM has been introduced to enhance comprehensiveness by combining two approaches: the FRAM-ES Model and the FRAM-Dynamic Bayesian Network. We aspire to contribute to the broader understanding of how we can harness human adaptability alongside advanced technological developments to create a more resilient system.

1.3 Limitation

This dissertation presents a comprehensive analysis of human adaptability and flexibility for establishing safety in everyday shipping operations. While our study provides valuable insights into this critical area of inquiry, it is imperative to acknowledge and transparently discuss the limitations that have shaped our research process and may impact the interpretation of our findings. The study was conducted at a single educational institution. The primary qualitative data was gathered onboard our faculty training ship Fukaemaru. In addition, ship handling simulation data has also been performed in our faculty facility with a very small number of participants. Consequently, the findings may not be fully generalizable to a broader population of seafarers in different working areas.

The research was conducted over a relatively short time frame, focusing on operations within Osaka Bay and ship handling simulator simulation. This limitation naturally restricts the breadth of information obtained regarding real-world activities. The study's scope and depth were further constrained by the available resources, including the number of participating professional seafarers and the level of technological tools at hand. Consequently, the data primarily relies on narrative descriptions, which inherently carry a subjective bias. Additionally, unforeseen external factors, such as the recent pandemic COVID-19 situation, have further impacted the data collection process.

1.4 Research Aims

In accordance with the background explained above, two aims have been formulated as a goal of this dissertation.

1. To elucidate the resilience potency of the shipping operation, specifically for ship navigation.
2. To demonstrate and propose a novel safety analysis of ship navigation based on resilience engineering framework by aiming the potency of increasing complexity of future ship operation.

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Chapter 2
Literature Review

2.1 Ship Navigation as a Complex Socio-technical System

The notion of socio-technical system embedded the recognition of interrelation between humans and technology in social context where in the work occurs. This term has a long development history which initially coined by Trist and Bamforth [28] and Emery [29] in 1950s. Socio-technical system theory explains the essence of understanding and improving organizational system design and performance by acknowledging interdependency of social and technical component in complex systems. Humans as the social component is eminent for its flexibility. In contrast, the technical component tent to be more consistent. Technology has an advantage in predictable tasks that demand consistent performance. If the task environment is unpredictable, then the human with support of proper tools is needed. Technology itself does occasionally break down, which makes them necessarily rely on human intervention. Therefore, the complementary recognition between human and technology is critical for overall system functioning [30].

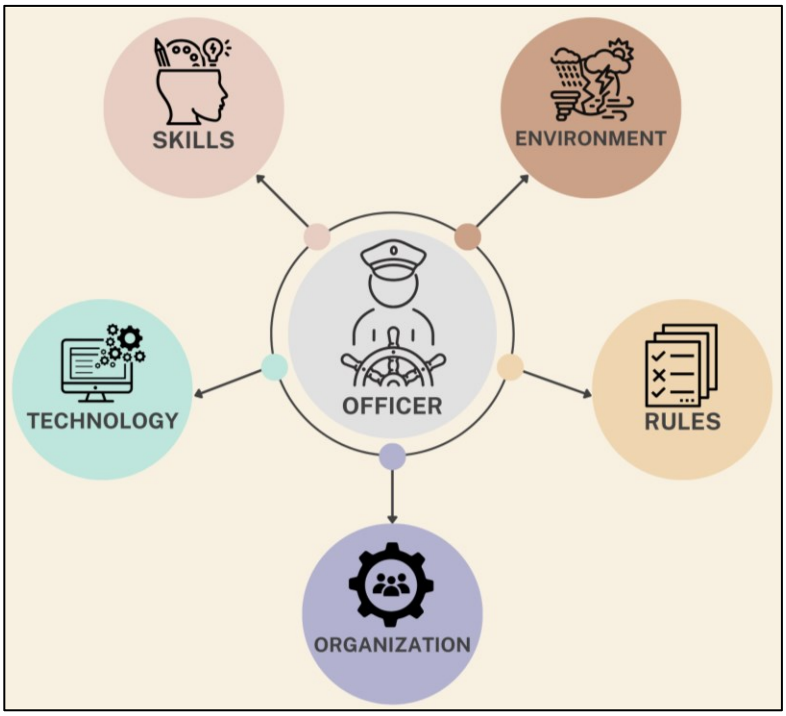


Figure 2.1. The components dependency in ship navigation.

In the heart of the vast, unpredictable expanse of the world's oceans, a ship sails every day, connecting distant shores, with skillful seafarers operating it. Ship navigation, often seen as a straightforward endeavor from the outside, reveals itself as a complex socio-technical system upon closer examination. The advancements of technology have evolved today's onboard work to interact with complex control centers, e.g., bridge control room, for monitoring, control, and track the process occurring on the ship. It implies to the rapid changing of human and social behavior that escalating the level of complexity by speeding adaptation and connectedness [31].

According to Holland [32], complex adaptive system shares three similar characteristics, including evolution, aggregate behavior, and anticipation. The interaction between different elements with varying individual attributes causes the system to be so hard to understand. In the case of shipping operation, the mother nature of marine environment contributes to the paramount portion of ambiguity from unpredictable weather patterns, ocean currents, and other ever-changing natural conditions. It escalates by the dynamic in ship traffic, unique port or channel geographical features, and applicable rules (local and international). In this interrelated work environment, the ship officer is at the center of the system, expected to handle the dynamics onboard as a controller, monitor, and decision-maker. Shipping operation, in specific context of ship navigation is a prime example of complex socio-technical system where the interaction between technical components, human factors, regulations, and environmental considerations is essential for safe and efficient maritime transportation.

2.2 Resilience Engineering Paradigm

There is no single definition to describe what resilience is in different fields of study. The English word "resilience" itself was brought from Latin word *resalire*, which verbatim means "to spring" [33]. The term "resilience" has a long history of use in physical science to denote the behavior of springs. Later, in 1973, C.S. Holling adopted this concept within the discipline of social-ecological systems to describe the ability of ecosystem to absorb and overcome adversity, enabling the system to continue functioning [34]. In a scope of reliability organization, the term resilience is firstly found in a paper written by Sutcliffe and Vogus [35]. Furthermore, the field of safety science has made its own significant contribution to this concept, primarily through the work of Hollnagel [18], [36]. This approach is currently recognized as Resilience Engineering (RE).

In RE paradigm, the resilience definition is evolving over time. In the book "Resilience Engineering: Concepts and Percepts" [18] is described as an intrinsic ability of system to maintain the stable state in the presence of continues stress or after a major mishap, such that the system able to continue the operation. This definition later updated in the book "Resilience Engineering in Practice" [36], aiming broader scope of resilience performance, not only emphasizes the threats or risks, but also the expected system output. It is described as the intrinsic ability of a system to adjust its level of functioning prior to, during, or following the presence of disturbance or changes, resulting in sustainable operation under both expected and unexpected operation. It indicates the focus in resilience engineering is resilient performance, rather than resilience as a quality or property or resilience as a comparison dichotomy of "A versus B."

The performance adjustment in RE has fundamental basis brough from the principle of efficiency-thoroughness trade-off (ETTO) [37]. Intuitively, an activity often done in limited availability of resources, e.g., time, information, materials, tools, energy, and manpower. In this case, the operator usually manages to meet the requirement of acceptable performance by adjusting the work execution prior to the current situation – *in a nutshell* to balance the presence demands and available resources. Thus, this adjustment ability can be described as a trade-off between efficiency and thoroughness. If the dominant concern is safety and quality, the trade-off may favor thoroughness over efficiency. In contrast, if the dominant concern changes to output, the trade-off favors efficiency over thoroughness. Through this principle, it being said that it is impossible for a system to maximize efficiency and thoroughness at the same time.

2.3 Focusing on What Goes Right

2.3.1 A Term of Safety-I and Safety-II

Initially, the term Safety-II introduced by Hollnagel [20] was to wider the understanding of traditional safety approach that in particular focus on incident or accident, which is later called as Safety-I. This classical viewpoint presumes that undesired outcomes stem from identifiable malfunctions within specific components: technology, procedures, human workers, and the organizations in which they are integrated. Within this framework, humans are frequently perceived as a liability or hazard due to being the most variable among these components. This perspective aligns with Safety-I, which concentrates on preventing accidents by managing potential sources of risk. Safety-I aims to minimize errors and deviations from standard procedures, emphasizing learning from failure events to enhance safety. These underlying assumptions have led to intricate and consistent system descriptions, facilitating the identification and resolution of malfunctions.

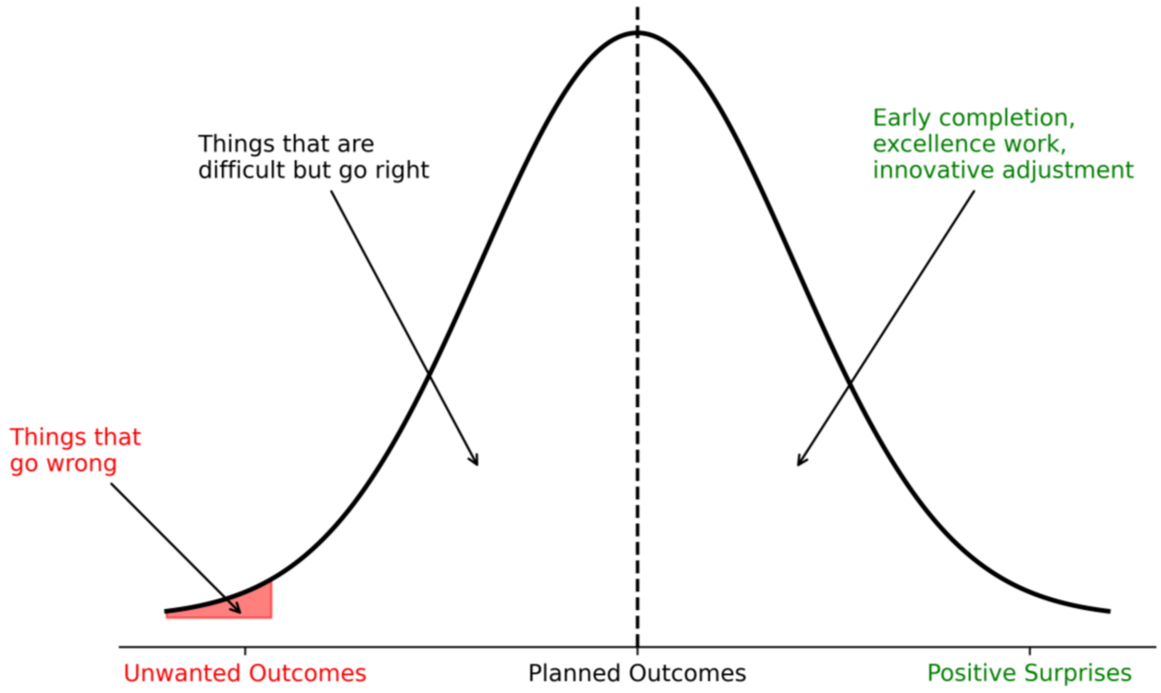


Figure 2.2. An illustration of event probability and safety focus.

However, the preceding sub-chapter has explained the theory of complex socio-technical systems and the challenges we face in managing today's system. Machines are comparatively more stable and easier to manage in contrast to humans. However, predicting the natural environment remains challenging. The configuration of complex systems cannot be effectively decomposed, and their functions are not bimodal, neither in detail nor in their entirety. Machines facilitate faster and easier human work. In turn, humans capitalize on this advantage by adapting the system's functioning in the event of machine breakdowns. Hence, it is the collaborative effort that extends the system's availability, highlighting the necessity for adaptable and flexible work.

This inspired an awareness of learning safety directly from successful events. Safety-II is proposed as a solution to expand the understanding of safety, emphasizing a system's ability to perform effectively under diverse conditions, as represented in Figure 2.2. It aims to understand how systems can function effectively even when facing unexpected conditions, variability, and changing circumstances. Safety-II focuses on learning from successful outcomes and ensuring they are replicated as frequently as possible. It recognizes that in complex systems, deviations and adaptations are constant, and safety often arises from these adaptations.

Table 2.1. Heterogeneity of performance variability for each function characteristics [38].

	Human	Technological	Organizational
Characteristic performance	Adaptive and flexible	Stable, reliable, and predictable	A support for human and technological function
Variability	Variable	Stable, slow degrading	Variable
Damping potential	Potential for performance variability damping	No potential for performance variability damping	Provide the means to damp performance variability

The purpose of understanding these terms is not to compare or solely contradict the safety perspective. Rather, Safety-I and Safety-II are complementary, enriching our comprehension of today's complex systems. The evolving system complexity over time not only introduces new potential sources of disturbance, but existing sources can also evolve. This implies that the system should not only prevent what could happen but also adapt to unexpected changes and search for opportunities for improvement.

2.3.2 Functional Resonance Analysis Method (FRAM)

The development of resilience engineering paradigm along with the introduction of Safety-II terminology [20], [39] have recently attracted attention in the field of safety research. This idea promotes a new point of view on safety by acknowledging safety as an emergent phenomena instead of a property of the system individual component. Therefore, FRAM [40], [41] has been introduced as the first attempt to implement this idea. This method emphasises the necessity to focus on how successful performance occurs in actual work.

FRAM uses a term function to describe the need for something to be done in the system. It classifies the function as either human, technological, or organisational. The FRAM has been developed with a focus on understanding the nature of a system’s normal functioning in everyday operations. To achieve this purpose, this method is based on four fundamental principles, including:

1. The principle of equivalence of successes and failures: the source of wanted or unwanted outcomes in sailing is a part of the working adjustment made by the operator. In this case,

failure is not viewed as a malfunction of normal system functions, which sets it apart from the nature of an event involving a functioning system (success). Instead, it is understood as the downside of an adaptation strategy that is a consequence of real-world complexity.

2. The principle of approximate adjustment: it explains that the complex environment of socio-technical systems causes work to not entirely align with the ideal prescription of working guidance. This implies that workers, whether as individuals or in groups, need to adapt their work performance to meet existing conditions, which may involve factors like resources, demands, opportunities, conflicts, and interruptions. Moreover, these adjustments tend to be approximate rather than exact due to limitations in system resources. This approximation of the work is owing to the operation, which predominantly goes well, and occasionally, it goes wrong.
3. The principle of emergence: the variability in performance during everyday operations is seldom significant enough to directly cause an accident or constitute a malfunction on its own. However, when the variability in multiple functions combines unexpectedly, it can result in disproportionately large variations in performance, leading to a non-linear effect. In this context, safety and failure within complex socio-technical systems are recognized as emergent rather than resultant phenomena. It is asserted that both safety and failure are capacities that emerge from the system as a whole and cannot be attributed to individual components within the system.
4. The principle of functional resonance: it describes the potency of detecting the unintended interaction from the dependency among functions through the phenomenon of resonance. The interaction of multiple functions has the potential to resonate, meaning they can strengthen each other and, as a result, cause one function's variability to become unusually high. The effects of this resonance can propagate through tight connections, which can be described as a resonance of the normal variability of functions, known as functional resonance. The resonance analogy underscores that this is a dynamic phenomenon and cannot be attributed to a simple combination of causal links.

The functions in FRAM have specific attributes known as aspects. There are six different aspects, including **I**nput (**I**), **O**utput (**O**), **P**recondition (**P**), **R**esource (**R**), **T**ime (**T**), and **C**ontrol (**C**) [40]. Descriptively, the Input is traditionally expressed as information, matter, or a command used by the function to produce the output. However, in the context of FRAM, Input also has another equally important meaning, which is that of an activator or initiator for a function. From a technical perspective, Input represents a change in the state of the environment that acts as a signal to initiate the function.

Output refers to the action of the function following the processing of information from other aspects, such as the execution of instructions from the Input. It can be observed as state changes within the system or in one or more output parameters. In addition, Output can be seen as a signal that starts a downstream function. The Precondition is a description of the condition that needs to be met before the function can begin. It's important to note that the Precondition, by itself, cannot initiate the function. As previously explained, it is the Input that has the capability to start a function. This straightforward explanation can help in determining whether a function's state should be characterized as an Input or as a Precondition.

A Resource is defined as something necessary for the function while it's in progress, e.g., a spoon for eating ice cream. It can represent matter, energy, information, skills, software, tools, etc. While Time could theoretically be considered a Resource, it has a unique status and is thus addressed as a distinct aspect. Control is the aspect that provides guidance to the function during the process of generating the intended output. This could take the form of a plan, a schedule, a procedure, a set of guidelines or instructions, rules, and more. Finally, Time aspect of a function encompasses the different ways in which Time can influence the execution of the function. This aspect includes representations that define time-related constraints such as temporal relationships, sequencing conditions, or duration, such as when a work must be completed before a specific point in time or within a certain timeframe. It is worth mentioning that these aspects' descriptions should take the form of nouns if they are single words or should start with a noun if they are short sentences.

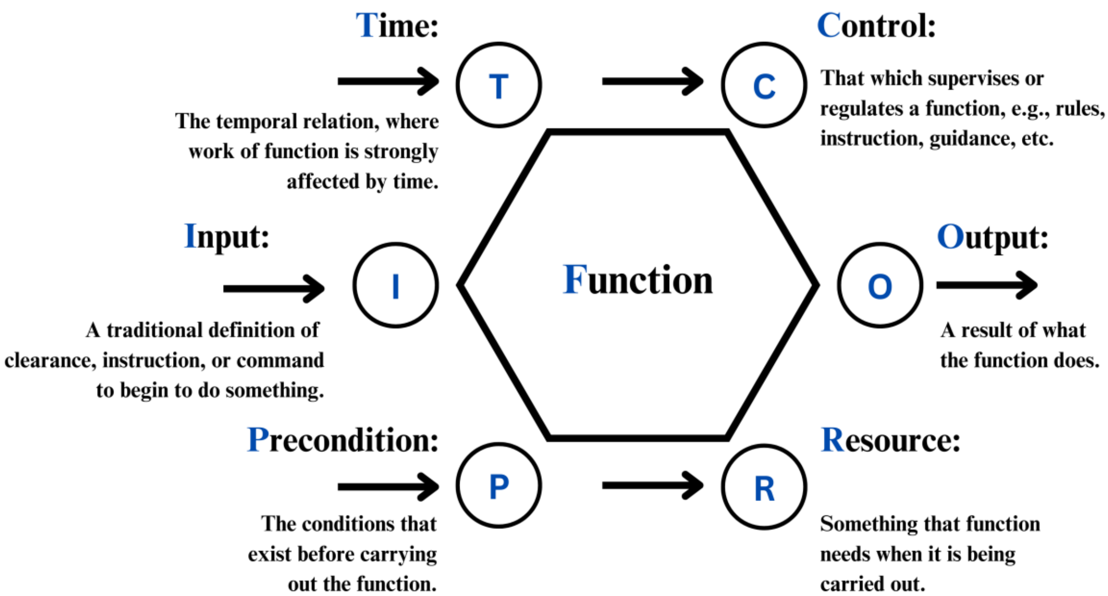


Figure 2.3. FRAM function and aspects representation.

Moreover, the function relationship, or *so-called* potential coupling is explained in two ways. First is general role of function, namely background and foreground function. The general role holds the definition of function in model as a whole. Intuitively, the foreground function is defined as the part that the study focuses on. In practical terms, this implies that the variability of the function may have consequences for the outcome of the event or process being examined. On the other hand, the background function can be assumed to be a function that does not vary, i.e., it can be considered constant during the event or the process under study. Therefore, this terminology reflects the relative importance of a function within the model. However, it's important to note that this status is not fixed. The focus of the study can change, which means that a function may transition from being a foreground function to a background function, and vice versa.

The second is temporal relationship that highlighting some specific functions to be observed, that is upstream and downstream functions. The analysis of the FRAM model involves examining potential couplings between functions step by step. This means that in a particular instantiation of the model, one or more functions are always in focus. The upstream function is defined as a function that is activated before the other function, and therefore, it can affect the other functions. The downstream function is defined as a function that is activated after the other function, and therefore, it can be affected by the other functions. This temporal relationship is crucial for describing the detectable signal of potential functional resonance, which can either enhance or reduce the system's performance.

2.4 Utilization of FRAM and Its Elaborated Version for Understanding Resilience in Ship Navigation

2.4.1 Understanding of Resilience Potency in Ship Navigation

The application of FRAM necessitates information about the actual work onboard, often referred to as *work-as-done*. This is a fundamental process to elucidate the resilience potency in ship navigation. Given that FRAM follows a qualitative approach, the initial strategy involves conducting field observations on board ships. The aim is to integrate the core concepts of FRAM into the assessment of ship navigation safety. This approach lays a robust foundation for proposing a FRAM model of ship navigation activities and its utilization in the rest of this dissertation. It underscores the essence of the resilience potency in shipping operations, particularly in navigation, and highlights the significant contribution of ship officers to this resilience.

2.4.2 Elaborated version of FRAM analysis for Application in Maritime Domain

This sub-subsection aims to enrich and broaden the FRAM assessment scope, contributing to the resilience engineering literature by proposing two separate modifications. First, it has the potency to integrate resilience engineering with a risk perspective. Second, it applies a temporal model to capture the state changes in system performance. The demonstration and application of these two distinct solutions are explained below.

2.4.2.1. Combining Risk Perspective and Resilience Concept

This elaborated version of FRAM is inspired by the work done by Logan et al. [42]. It is almost two decades [18] since the resilience engineering paradigm was introduced in the field of safety science. Despite the pros and cons arising due to this agenda, it sparks discussions for further development of safety assessment. Logan et al. argue that resilience and risk are both important ideas which can complement each other. One of the critical work that in line with this statement is addressed by Aven [43]. The crucial issues discussed in his work involve the potential incorporation of aspects of uncertainty and risk in FRAM modeling. This is not for the purpose of accurately obtaining risk estimation but rather to improve the understanding of safety and support decision-making. As a result, an important message is conveyed through this combination, acknowledging the key to cooperating resilience and risk concepts: "A system is judged resilient if the risk of not achieving the desired functionality is sufficiently low" [44].

The application of this cooperative assessment in this study aims to enhance the FRAM analysis by incorporating objective measures in the form of risk values. The critical consideration for selecting the risk assessment method to support FRAM analysis is its ability to offer time-based evaluations for individual case studies. Additionally, the chosen method must be capable of utilizing the characteristics stated to classify FRAM function performance, namely time precision, distance, and ship heading. Thus, a method known as the environmental stress (ES) model has been selected.

An ES model is a quantitative model proposed for evaluating the difficulty in ship handling because of the topological constraints or traffic congestion around the ship (Inoue, 2000; Inoue et al., 1998). However, in this study, topological constraints, such as islands, breakwaters, and buoys, were not considered. Instead, the *ES* was described only by the traffic conditions related to the target ship presented in the simulation. The degree of danger perceived by the ship officer was expressed by the existence of the target ship within a course range of −90° to +90° from the heading direction of the participant's ship. Consequently, the risk index perceived by the participants can be calculated as follows:

$$SJ_s = \alpha\left(\frac{R}{L_m}\right) + \beta \tag{1}$$

$$\alpha = 0.0019 \times L_m \tag{2}$$

$$\beta = -0.65 \times ln(L_m) - \gamma \tag{3}$$

where SJ_s is the subjective judgment of ship officers in relation to time to collision with target ships; R is the relative distance between the participant's and target ships; L_m is the average length of the participant's and target ships; α is a coefficient determined by the combination of the size of the participant's and target ships; β is a coefficient determined by the relative bearing of the participant's and target ships; γ is a coefficient determined by the ship-ship encounter situation, such as 2.07 for crossing from the starboard side, 2.35 for crossing from the port side, 2.07 for a head-on situation, and 0.85 for an overtaking situation.

The *ES* value was derived as the sum of all potential SJ_s within a course range of ±90°. This can be expressed as follows:

$$ES_s = \sum_{i=-90}^{90} (SJ_s)_i \tag{4}$$

The *ES* value ranged from 0 to 1000, where 0 and 1000 indicate a very safe and dangerous situations, respectively. This risk value has been widely applied to assess the safety level of marine traffic [45], [46]. Generally, the *ES* value is applied to indicate the necessity for collision avoidance manoeuvres. It can also be used to indicate the congested level of a waterway. However, in this research, the *ES* value is specifically utilized for the individual evaluation of participant performance in ship manoeuvring simulation as a complementary support for FRAM analysis.

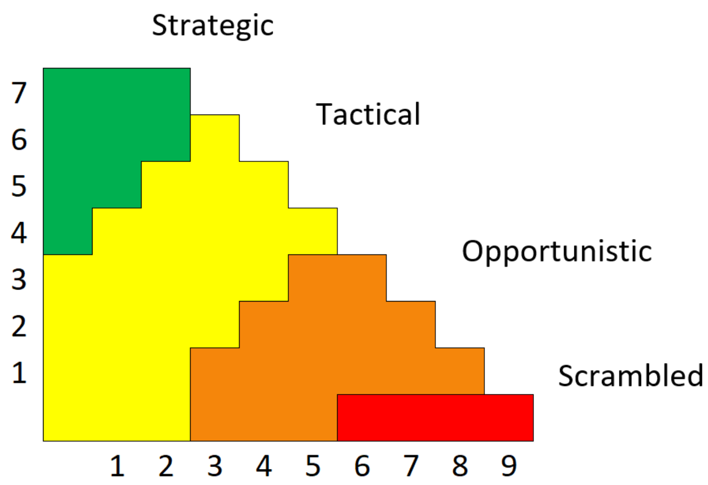


Figure 2.4. Relationship between control mode and common performance condition.

2.4.2.2. Probability on FRAM: the Application of Dynamic Bayesian Network

This method combination aims to provide an explicit expression for function performance. The understanding of changes in performance along the voyage led to the idea of implementing a temporal model to depict this situation. Therefore, a Dynamic Bayesian Network (DBN) is selected as a solution. The FRAM function performance is divided into four categories: strategic, tactical, opportunistic, and scrambled, as shown in Figure 2.4. A case study has been chosen to demonstrate the application of this FRAM-DBN analysis. Based on the information from the case study, changes in performance categories are determined through assessed performance variability in functions, considering the function's phenotypes such as time, precision, distance, and heading. Furthermore, it can also illustrate how the performance of one function affects the other functions in a given instantiation through couplings.

DBN is an extension of the Bayesian Network (BN) with the ability to handle temporal dependency among nodes that change over time. This advantage makes DBN suitable to be applied for establishing an explicit representation of the dynamic in performance of ship officers during encounter events. DBN presents a pair of time slices of BN ($X_{t-1} \rightarrow X_t$), where X_{t-1} is the initial BN that defines the initial probability of $P(X)$, and X_t is the BN in the next time slice that contains the conditional probability of two-time slice. This state transition probability can be expressed as:

$$P(X_t|X_{t-1}) = \prod_{x=1}^{n_t} P\left(X_t^i|Pa\left(X_t^i\right)\right) \quad (1)$$

where *P(X)* is the set of variables; $X_t^i$is the *i*-th node of time slice *t*; $P_a(X_t^i)$ is the parent node of X_t^i ; *nt* is the number of nodes in the t-th time slice. In order to solve this mathematical equation, the SMILE modeler provided by BAYESFUSION has been applied in this work. In addition, the DBN modeling has also been done using the GeNIe software.

Chapter 3
Field Observation (Direct onboard observation of Fukae-maru)

3.1 Introduction

The previous chapter discussed the related literature that supports the scientific process and analysis performed in this dissertation. This chapter contains the fundamental basis of FRAM application to elucidate the resilience potency in shipping operations. It includes the proposed method, data collection, and analysis of the everyday operation of the ship in a particular context being examined. Consequently, this chapter proposes a functional model of ship navigation activities and emphasizes the essence of human adaptive and flexible performance for system resilience.

The initial application of the resilience engineering perspective in this research pertains to the safety evaluation of navigation abilities performed by an Officer for navigating a training ship in a coastal area. The term Officer refers to the authorized seafarer overseeing navigation operations at sea, in ports, and during anchoring. Employing the functional resonance analysis method (FRAM), aligned with this resilience engineering perspective [41], has been selected as the primary method for this study's analysis. Numerous studies have applied FRAM to analyze accidents in the maritime domain [47]–[51]. Additionally, its application in seeking safety during routine operations in the maritime domain is notable. For instance, one study analyzed resilience in everyday vessel traffic service (VTS) operations [52], while another explored complexity in ship-mooring operations at the quay [53]. A study on raft fishing has presented the possibility of measuring safety from the perspective of Safety-II [54]. The resilience engineering perspective has received recognition in enhancing maritime safety, primarily noted for its prevalence in reanalyzing maritime accidents [55]. Despite this, it has yet to be employed for assessing the actual work done by ship officers on the bridge deck. Given this situation, it is considered necessary to adopt further a resilience perspective in the actual everyday operation of the ship. This chapter aimed to present the resilience potency inherited in today's ship navigation through FRAM analysis.

3.2 Research Methodology

This sub-chapter describes the set of processes used in this research. The method applied in this study is qualitative, aiming to develop ideas to explain how safety emerges in the routine operations of a ship through the lens of Safety-II. To develop comprehensive insights, an onboard observation of the Fukae-maru was carried out, providing valuable information about the activities of ship officers. The observation was conducted on five different days, totalling approximately 35 hours of sailing. Furthermore, the Functional Resonance Analysis Method (FRAM) was utilized to analyze and construct a systematic model of officer activities aboard the ship. This analytical approach seeks to elucidate how the variability performance of officers contributes to safety in the everyday operations of the ship.

3.2.1 Data collection and FRAM application on ship navigation

The primary data for this study were obtained through direct observation, involving the recording of videos and taking photos on board the training ship Fukae-maru, which is owned by Kobe University. Complementing this visual data, a direct semi-structured interview was conducted to validate and enhance the understanding of the observed situations [56]. The utilization of qualitative data in this form allows for the documentation of various aspects of an Officer's onboard experience, including activities, behaviors, and any observable elements related to ship navigation [57]. This qualitative approach is valuable as it captures the nuances of the Officer's actions within the specific context of ship navigation. The inclusion of naturally occurring data is essential for the Safety-II approach, as it necessitates a deep understanding of how tasks are carried out in practice [56]. By collecting data in real-life scenarios, we can gain insights into the intricacies of the Officer's work and the contextual factors that influence decision-making and actions. This firsthand and holistic perspective is crucial for comprehensively applying the Safety-II framework, which seeks to go beyond traditional safety assessments by examining the adaptive capacities and responses in the real-world environment of ship navigation.

Moreover, the collection of data was conducted with approval from both the Ship Master of the Fukae-maru and the designated Kobe University representative, who served as the ethical and legal oversight for all crew members. The observational data has been meticulously anonymized to prevent any connection of information to individual persons. The onboard team comprises six Officers, including the Captain, Chief Officer, Second Officer, Third Officer, and two Junior Third Officers. Their cumulative experience ranges from less than five years to over ten years, providing a diverse perspective. Particular attention has been given to the activities of key roles, including the Captain, Officer of the Watch (OOW), and Helmsman, with a focus on both technical and social interactions inherent to these positions. It is important to note that the data collected in this study exclusively presents the primary activities of the Officers on board, excluding any information related to cargo work. In addition, the observation took place during the ship's navigation in a coastal area within Osaka Bay, Japan, where reporting to shore representatives, such as port authorities, was not required.

The essential insights derived from onboard observation were transformed into a key function and modelled through the application of the FRAM model. Considering the specific activities of the Fukae-maru during the observation period, successful ship navigation is defined as the system's ability to operate in a manner that fulfils the educational needs of the students learning navigation techniques. Additionally, it entails the ship safely sailing and returning to the berthing area without encountering any issues such as collisions, damage to the ship's structure, or the loss of human life. Therefore, the functional model of ship navigation proposed in this study attempted to obey the purpose of the system, seeking to understand how the system can achieve these defined goals.

3.2.2 Observation General Overview

Fukae-maru is a training ship used for academic purposes, including practical learning for cadet students, research, and experiments. With a compact size boasting an overall length of around 50 meters, it is specifically designed for short voyages. The nonparticipant observation technique [58], [59] was employed to observe Officer onboard activities, with the observer refraining from direct participation in the observed tasks. This approach is crucial for capturing the spontaneous nature of activities, enabling a nuanced understanding of participants' interactions within their work environment. To mitigate potential data quality issues associated with this technique, a combination of methods such as interviews, field notes, photos, video recordings, audio recordings, and extended observations on different days was employed. Ethical considerations, particularly regarding the authority to describe observed events, were addressed through ongoing discussions between participants and the observer to collaboratively construct an accurate portrayal of the phenomena under observation. The onboard observation commenced at around 9:40 a.m. JST and concluded at approximately 04:40 p.m. JST, spanning three distinct weather conditions: a sunny day with clear skies, a cloudy day with light rain, and partially cloudy conditions without rain. Visibility remained favorable throughout these situations.

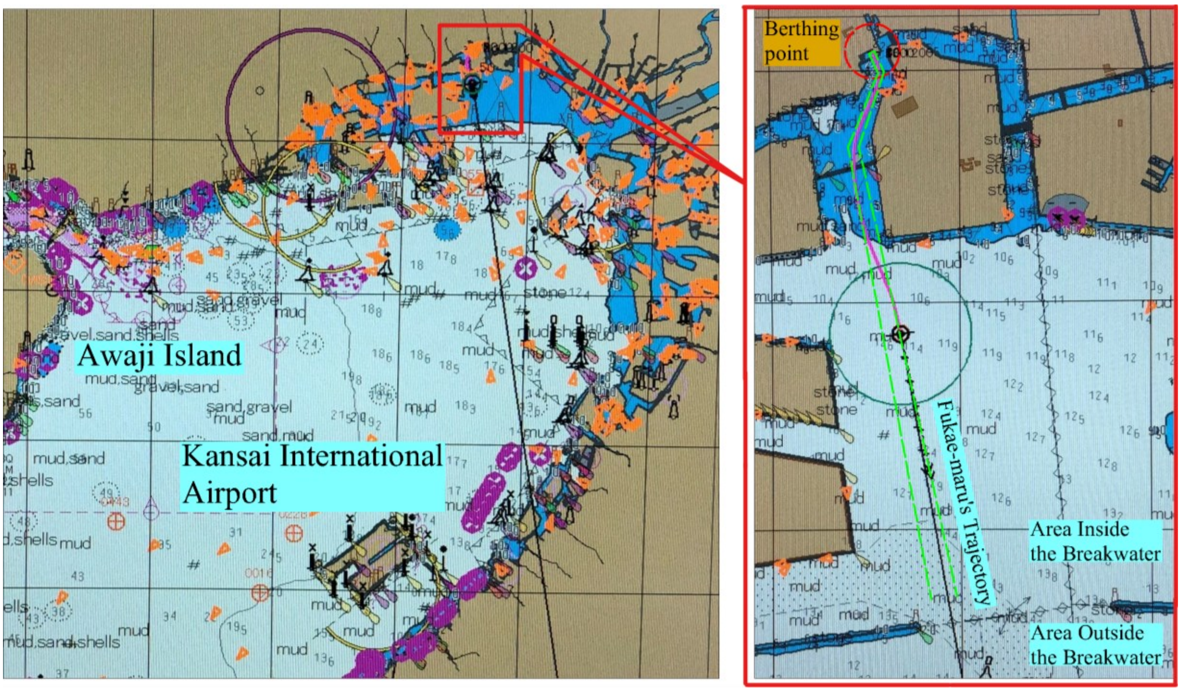


Figure 3.1. An overview of Fukae-maru's voyage during the observation (adapted from [61]).

Figure 3.1 shows a visual representation of Fukae-maru's journey within the Osaka Bay area. The voyage commences as the ship departs from its berthing area, marked by the red dashed circle. Following departure, the ship gradually navigates through the Kobe Port area, progressing beyond the breakwater indicated by the dashed green line. The ultimate destination beyond the breakwater lies either southwest, in proximity to Kansai International, or west, near Awaji Island. Regardless of the chosen route, Fukae-maru concludes its voyage by returning to its initial berthing area. The comprehensive navigation activity is conveyed in a narrative format, derived from photos, videos, and audio (interviews) recorded during the observation [57], [60]. Rather than providing a daily narration, the information has been coded based on recurring patterns and presented as a summarized overview.

3.3 Actual Onboard Work of Fukae-maru: A Narrative

Preparation is inherently vital for the commencement of activities, with certain aspects even addressed well in advance. Elements such as voyage planning and briefings are typically conducted prior to the first day of the voyage, generally performed once for a set of scheduled voyages. In addition, the weather information is also provided in advance and updated over time. The early preparation done by the Officer and engineer is to make sure that all materials on the checklist have been fulfilled. For example, this includes verifying the functionality of electrical equipment, confirming the ship's stability, and conducting alcohol checks. It is important to note that the study's scope does not delve into a detailed examination of these early preparation activities.

The primary observation occurs within the bridge deck, where the operational sequence initiates with the ship departing from the berthing area. In the beginning, the deck department is organized into three teams. The Captain and the Third Officer, serving as the Helmsman, remain inside the bridge deck. The First Officer and the Second Officer, each accompanied by a Junior Third Officer, position themselves at the bow and stern of the ship, preparing for unmooring duties. Within the bridge, the engine is primed, and control is transferred to the navigation panel operated by the Helmsman. From now on, the Helmsman assumes responsibility for managing the engine, steering wheel, and thruster in accordance with the Captain's orders. Once the bow and stern teams notify the Captain of the completion of the unmooring tasks, the Captain issues instructions to the Helmsman to initiate slow movement. This stage involves rapid communication and feedback between the Captain and the Helmsman. In this dynamic setting, the Captain's decisions are significantly influenced by geographical constraints and environmental factors. To overcome these challenges, the Captain receives additional assistance from the First and Second Officer’s team- for ship position information. This collaborative interaction persists for approximately 500 meters as the ship transitions away from its berth.

Fukae-maru then continues to sail in the Osaka Bay area. At approximately a nautical mile from the berthing area, watch responsibility transfers from the Captain to the OOW. The OOW role is performed alternately between Officers, excluding the Captain. Before handing over the watch responsibility, the successor of the watch Officer should immediately learn about the current vicinity situation. Then, the successor should confirm the information they collected with the previous watch Officer while handing over the duty. The primary concern in navigating the ship in Osaka Bay is the traffic volume because two major ports, Osaka Port and Kobe Port, exist in this area. In contrast, shallow water is considered a minor concern because the draft of Fukae-maru is small.

The Officer’s main activity along the voyage is the observation of the ship’s vicinity. The watch Officers are responsible for finding a target ship or other obstacles that may create dangerous situations with the ship and maintaining the ship’s course. If a target ship exists, the first thing that the OOW typically does is check the ship’s relative bearing with that target—this is followed by obtaining more information, such as the target’s name, speed, heading, and closest point of approach (CPA) through RADAR. The learning process then moves forward to expect that target's intention, that is, whether the target threatens the ship or not; then, an action is decided upon. Before that action is taken, some questions may emerge. When is the right time to start giving instructions? Where is the target? At what distance with the target should the action be taken? What kind of action should it be? The situation becomes more complex when the environment is involved. For example, ocean tides and currents may affect ship movement, and this should also be considered by the OOW. Unfortunately, the answer cannot be obtained explicitly. However, there is a rule that may be followed: earlier is better for recognising the target ship—but the action should not be decided too early or too fast.

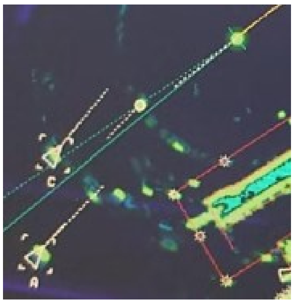
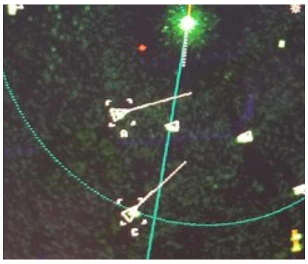
Fukae-maru concludes her voyage by returning to the berthing area. On the return journey, onboard activities, including monitoring the vicinity and transferring the Officer of the Watch (OOW) responsibility, persist and are reiterated. Upon entering the breakwater, approximately a mile from the berthing area, the Captain assumes watch responsibility from the OOW. The remaining Officers divide into teams to prepare for mooring at the bow and stern of the ship. While the procedures for departure and arrival are analogous, they are executed in reverse during the return journey. Finally, Fukae-maru successfully completes her operation and safely arrives.

3.2.1 Dynamic changes in marine traffic

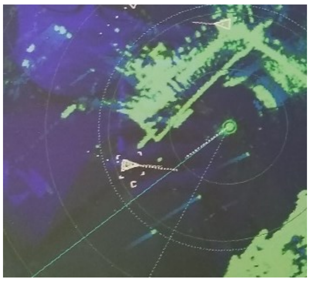
Although marine traffic may not exhibit the same level of chaos as road traffic, it remains a dynamic and complex system. Instances illustrating this dynamism were observed in specific situations during the activities of Fukae-maru. The variations of this dynamic nature in ship navigation are outlined in Table 3.1, where three carefully chosen conditions are presented. These conditions were selected based on their richness and relevance to the research question at hand. The chosen scenarios summarize crucial factors such as environmental conditions, geographical limitations, the human element, and technical aspects, offering a comprehensive and relevant context for analysis.

The whole working adjustment made during Fukae-maru's activities are visually presented in Figure 3.2, emphasizing two key objectives. Within the context of this figure, the sailing activities were designed to instruct students on navigating the ship using landmarks along the coast and aligning with the coastline direction. In addition to ensuring the safe navigation of the ship, the Officer also had the responsibility of adhering to the planned sail adjustments to meet the educational needs of the students. Evaluating the bridge team's performance involved comparing the passage plan with the actual trajectory and assessing whether the planned-

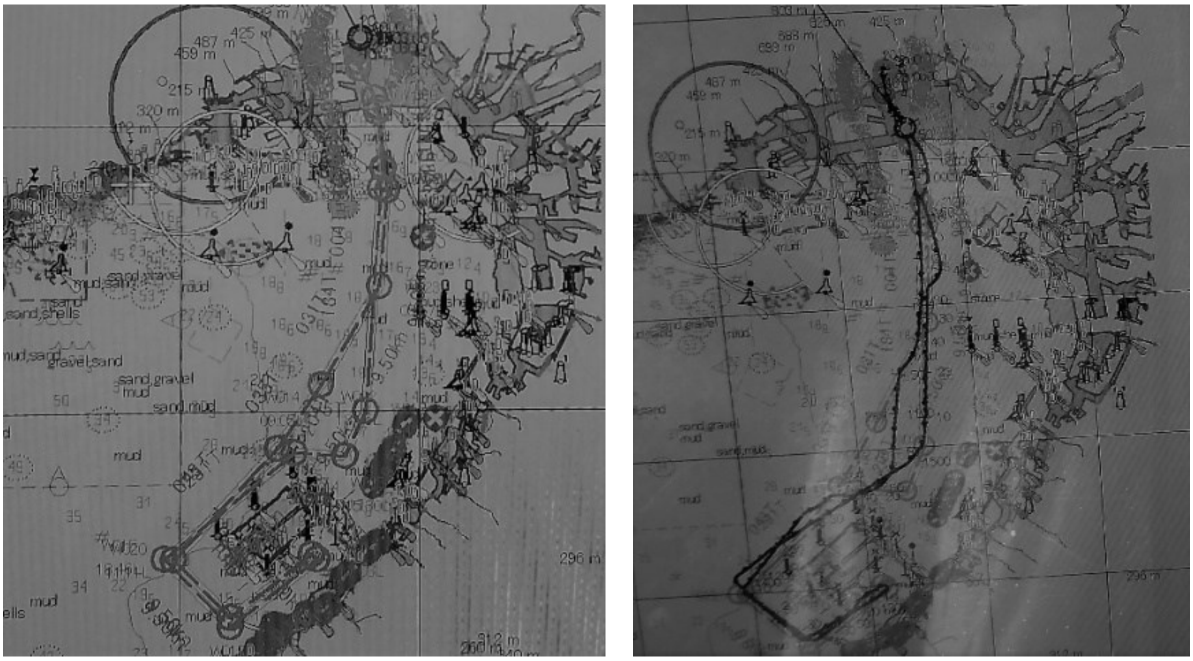
Table 3.1. Dynamics in ship-encounter situation during the observation (adapted from [61]).

Actual captured situation	Description of the situation
First case 	This encounter situation was captured on the first day of observation. In this situation, the OOW passed between two ships, namely Target A and Target C. Fukae-maru was heading southwest at 226. Meanwhile, Target A and Target C were heading northeast at 040 and 027, respectively. In this head-on situation, Target C was not threatening, but Target A was. The solution seems clear here. There is enough space between Target A and C. However, that was not the case. At that time, Target A was slowly approaching Fukae-maru, and heading straight was not a good decision. Therefore, the OOW decided to wait before changing Fukae-maru's heading to 230. The OOW said that *patience* is essential to cope with this situation. After approximately 9 min of observation, the OOW slowly turned the ship's heading at a particular distance from Target C to avoid Target A. Finally, those two targets were passed safely.
Second case 	This encounter situation was captured on the fourth day of observation. Fukae-maru was in a crossing situation with a ship called Target A. In this situation, the OOW could freely alter the course to the starboard side, as regulated in the COLREG rules 15, because the encounter area is wide enough. However, the real challenges emerged from the environmental situation. There was a drizzle, and it was a windy day with good visibility. Therefore, the OOW should carefully calculate the distance and time to start the action by considering the influence of ocean tides and wind. Approximately 5 min after the OOW first spotted the target, they started the action and gradually changed the ships heading to the starboard side. As a result, Target A was safely avoided.

continuation of Table 3.1.

Third case 	On the fifth day of observation, Fukae-maru was sailing along the east side of the coastal area of Osaka Bay. This crossing situation between Fukae-maru and Target C happened when Fukae-maru reached her final point near Kansai International Airport. The OOW said that this was a difficult situation. According to the COLREG rules 15, the OOW should go to the starboard side and meet target C port-to-port. However, the OOW could not change the course to the starboard side because there is a restricted area around Kansai Airport that ships are prohibited from passing through. At that time, the OOW decide to lower the ship's speed while slightly turning the ship's course to the port. This action was done because it is hard to notice the change in another ships' speed. The effective way to confess our intention is by making slight changes in our heading. This was in accordance with COLREG 2(b): work-as-intended is not always work-as-done. Moreover, the OOW was also trying to allow a space to meet starboard-to-starboard. This action was taken soon after the OOW realised the existence of Target C. Eventually, Target C responded as expected by changing its course to the port side and safely meeting starboard-to-starboard.

-activities were executed within the designated time frame. Notably, the observations revealed that each sailing activity consistently concluded promptly according to the plan, spanning from 9:40 a.m. JST to 4:40 p.m. JST. This observation implies that the OOW provided manoeuvring solutions that successfully guided the ship through a successful operation.



(a) (b)

Figure 3.2. (a) Passage plan and (b) actual passage on day 5 of the observation (adapted from [61]).

3.4 FRAM Application: Building Model and Analysis

Table 3.2. The function of ship navigation activities (adapted from [61]).

Background Function	Foreground Function
<Briefing>, <To perform checklist>, <To get weather information>, <To pay attention to VHF radio>, <To board the ship>, <To follow the rules>, <To arrive at the docking area>	<To get ready for sailing (by Captain)>, <To start sailing (by Captain)>, <To monitor (by Captain)>, <To monitor (by OOW)>, <To Communicate with deck department>, <To communicate with engine department>, <To do mooring/unmooring duty>, <To do last check and hand over the engine control>, <To do direct lookout>, <To watch electronic devices>, <To provide additional position information>, <To maintain ship direction>, <To decide action (make judgment)>, <To decide action (leaving/entering the berthing area)>, <To control the rudder/engine>, <To control the rudder, thruster, and engine>, <To manoeuvre>, <To continue sailing>

This sub-chapter contains the creation of a FRAM model for ship navigation and the subsequent analysis results. While qualitative observations provided a broad overview of how Officer performance contributes to the safe and efficient everyday operation of the ship, it lacked a systematic representation of how the system consistently achieves its intended outcomes. To enhance comprehension, the FRAM model was employed to describe the functions and their interdependencies within the system. Within the study's scope, two FRAM models were utilized—an overarching model capturing the entirety of the ship's operation and a specialized model specifically focused on ship maneuvering.

3.4.1 FRAM model for a whole sailing activity

A graphical representation of functions and their dependencies for the entire operation of Fukae-maru is provided in Appendix 1. The ship operation is segmented into two primary situations: entering and leaving the berthing area and sailing inside and outside the breakwater. Figure 3.3 presents a partial view of the complete FRAM model, specifically focusing on the departure process. The comprehensive model comprises 20 foreground functions and 7 background functions, as detailed in Table 2. While the apparent number of functions may seem high, certain functions are repeated across different situations to prevent looping relationships in the presentation of function dependencies.

Highlighted in grey, the functions denote the preparation process. Notably, the Captain's role is distinctly represented in the model. The <to get ready for sailing (by Captain)> function serves as a downstream function receiving inputs across various aspects and, simultaneously, acts as an upstream function providing inputs for two other functions. This illustrates how the resonance effect can emerge and propagate swiftly through this function. However, a detailed examination of interactions among functions in this process was not conducted within the scope of this analysis.

The departure and arrival processes are generally considered equivalent as they involve the same set of functions. These functions encompass red-labelled tasks related to the Captain's responsibilities, blue-labelled tasks associated with the Stern and Bow Team, and yellow-labelled tasks linked to the Helmsman's duties. These functions operate synergistically and exhibit interdependence, establishing a unique relationship. Notably, functions such as <to decide action (leaving the berthing area)>, <to provide additional position information>, and <to control the rudder, thruster, and engine> highlight the clear emphasis on teamwork. Furthermore, the function's aspect elucidates how downstream functions utilize each output of the upstream functions. In this context, it is evident that the output of the Stern and Bow Team's work is continuously utilized to assist the Captain's work (resource (R) aspect), producing an output for the Helmsman (standard input (I) aspect).

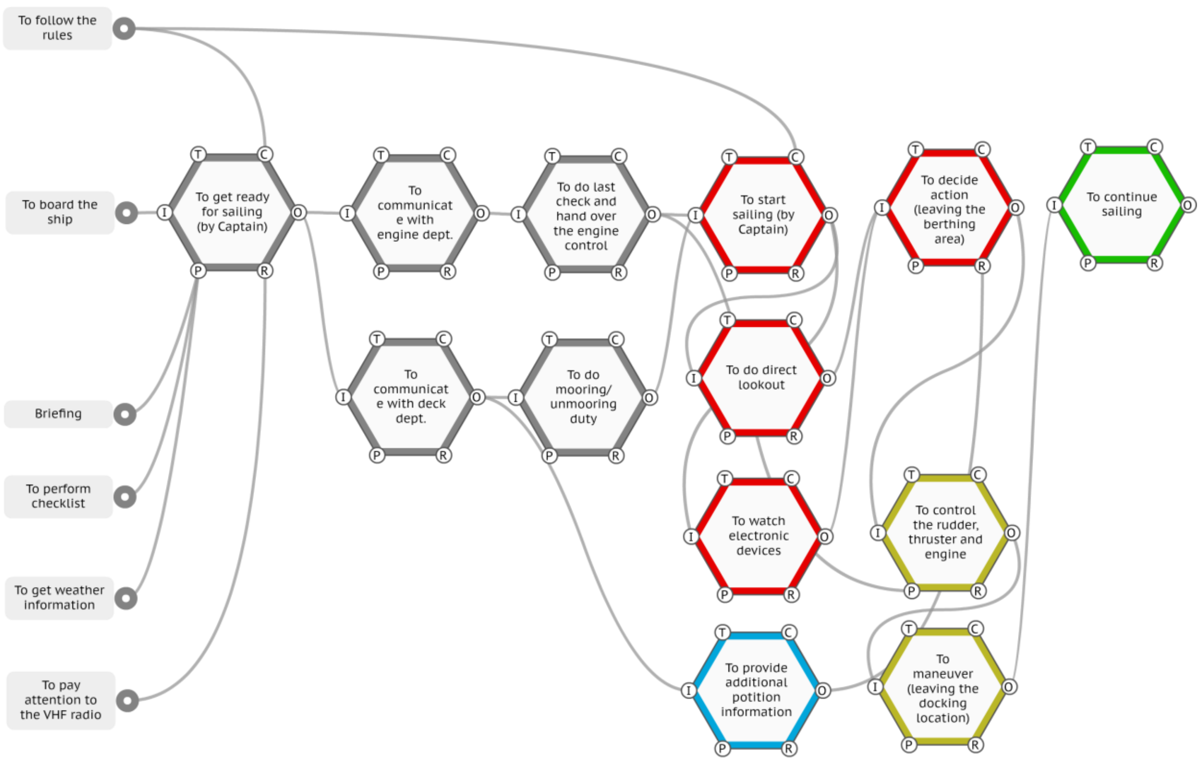


Figure 3.3. FRAM model for departure process of Fukae-maru (adapted from [61]).

3.4.2 Dynamic FRAM model for ship-ship encounter situation

The development of the FRAM model is expanded to address the specific context of ship navigation. The second model, shown in Figure 3.4, is designed to structure the dynamics of maneuvering during ship encounters. This model specifically focuses on the roles of the Officer of the Watch (OOW) and the Helmsman in creating a safe and effective avoidance process. The context for this model was derived from the information detailed in Table 3.1. Encounter situations occur in a distinct segment of the voyage and endure for a specific duration, resulting in changes in function performance over time that cannot be overlooked. As a result, the functions are presented repetitively to accommodate these changes. Additionally, for more precise classification, the model is divided into four stages: initial stage, follow-up stage, continuous stage, and final/steady stage.

The functions <to monitor (by OOW)>, <to do direct lookout>, <to watch electronic devices>, and <to maintain ship direction> possess critical points for the monitoring and learning processes in this encounter situation. These processes allow the system to properly decide an action (initial response) through the <to decide action (make a judgment)> function in the subsequent activation. Moreover, the system starts to anticipate the potential event that may occur in the future. The dynamic system propagation can be presented in two ways. First, if there is no threatening target ship, the system will leap to the follow-up and continue stages and directly start the steady stage. In this case, the dashed green line coupling shown in Figure 3.4 will directly change into a solid line.

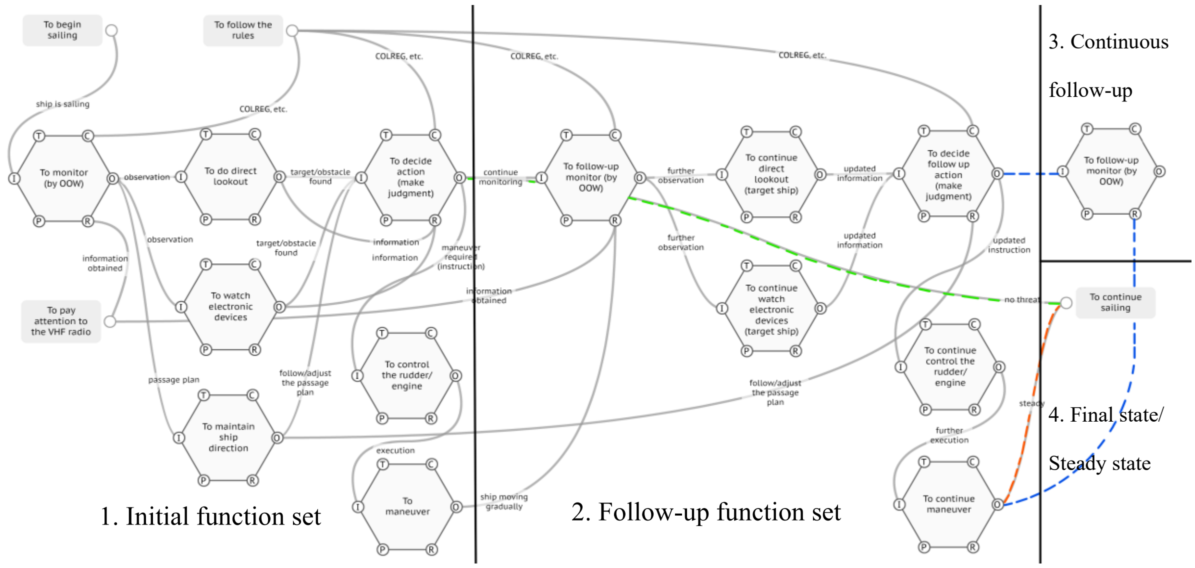


Figure 3.4. Dynamic FRAM model for specific ship encounter situations.

Alternatively, if there is a threatening target ship, the monitoring and learning processes will be repeated, and the system will be at the continuous stage. Four functions, including <to continue direct lookout (target ship)>, <to continue to watch electronic devices (target ship)>, <to decide follow-up action (make judgment)>, and <to continue to control the rudder>, play a critical role at this stage. The complicated situation requires the OOW to make many manoeuvring decisions to keep the ship safe. This causes multiple repetitions in the continuous stage. In summary, the continuous stage is a repeated follow-up stage before a steady stage (final) can be reached.

Furthermore, this dynamic functional model expresses the four potencies inherent in a resilient system. Gaining a nuanced understanding of the interplay between these potencies involves expressing them in a sequential order. The Officer's navigation of the ship starts with the sharp monitoring of the ship's vicinity, progressing to a comprehensive understanding of the current situation. It is at this point that patience becomes critical in deciding on an effective and safe maneuvering action. Once the decision is reached, the Officer must then initiate anticipation for follow-up actions and prepare for potential future encounters. Consequently, the likely sequence of these potential relationships in ship navigation can be summarized as "*to monitor and learn, then respond and anticipate.*"

3.4.3 Performance Variability of Ship Officer

Performance variability is defined as the system's capacity to meet performance demands within a dynamic operational setting. In this context, the Officer is recognized as the key figure responsible for local adjustments during the operation. As changes occur, the Officer's role is crucial in maintaining the system at the level of normal functioning. Consequently, the system is anticipated to effectively confront any disturbances and successfully achieve its primary goal of safe navigation.

Variation in function performance can manifest through internal (endogenous) factors, external (exogenous) factors, and potential couplings between functions. In ship navigation, the Officer's performance and external influences, such as environmental conditions, play a pivotal role. Therefore, both endogenous and exogenous variabilities significantly impact a function's output. In addition, potential variations in performance can arise through the potential couplings illustrated by the FRAM model.

The outputs of a function's work, whether deemed "wanted" or "unwanted," can be explained by examining the interaction among various sources of variabilities. To categorize different manifestations in the variability performance output of a function, three phenotypes were selected: time, precision, and distance. The functional model outlined in Appendix 1 highlights the necessity for robust teamwork during departure and arrival processes to ensure a successful operation. Specifically, the <to decide action (leaving/entering the berthing area)> function emerges as a critical point where functional resonance holds the highest potential. This function is subject to potential couplings from three upstream functions, as well as exogenous and endogenous variabilities to and from the function itself. Consequently, the amplifying effect resulting from this functional resonance may lead to the system functioning too late, imprecisely, and too close.

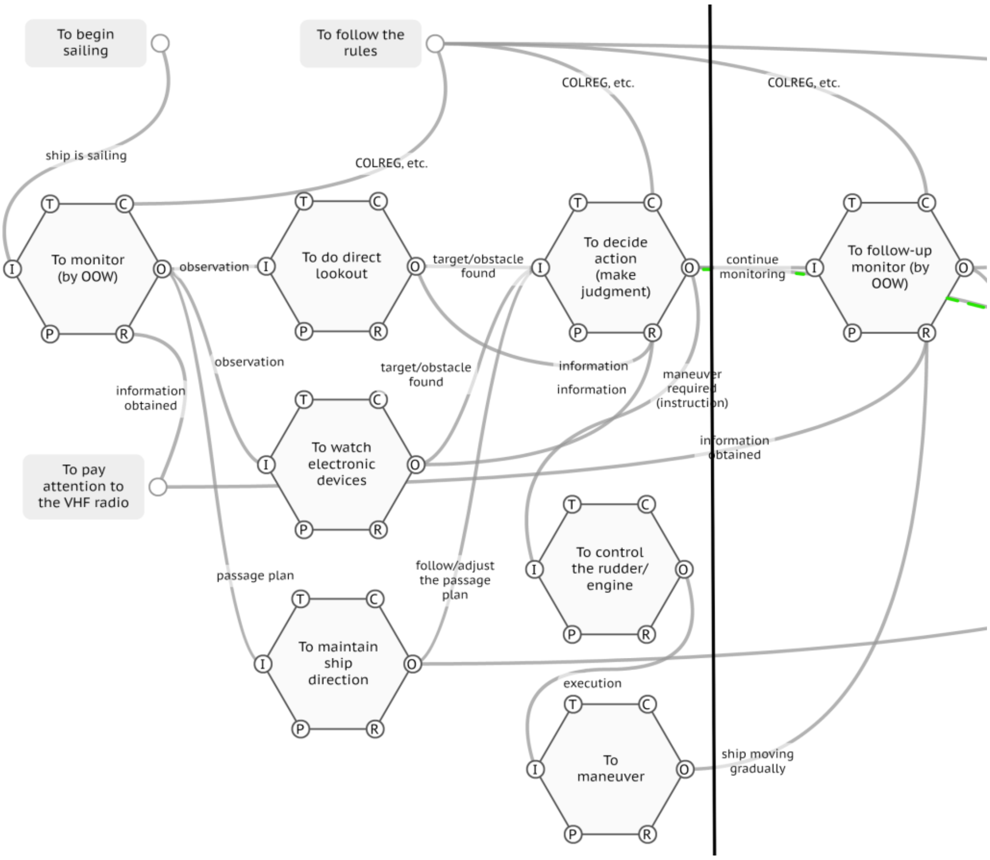


Figure 3.5. The initial function sets for the Dynamic FRAM model of ship-ship encounters.

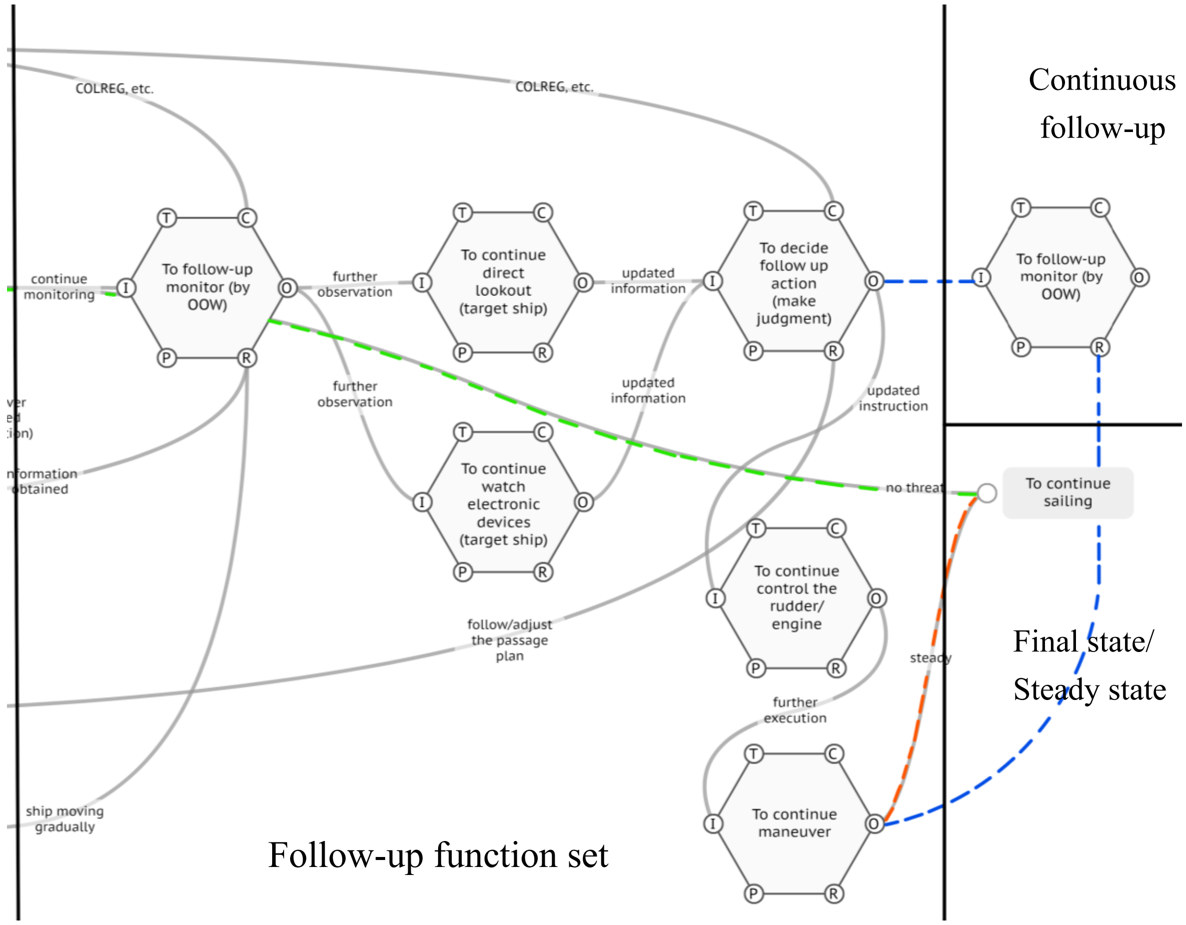


Figure 3.6. The follow-up function sets, continuous follow-up sets, and steady state.

The endogenous variability in performance associated with the Captain's responsibilities is particularly sensitive to precision, distance, and timing. During departure and arrival activities, in addition to collecting data independently, the Captain must collaborate with the Stern and Bow Team and the Helmsman. This collaboration introduces the potential for the function to generate imprecise, delayed, or too-close outputs. Furthermore, the endogenous variability performance linked to the Stern and Bow Team can be characterized in terms of timing and distance. As the team acquires information on the ship's position through direct observation, it is imperative to periodically report this information to the Captain throughout the departure and arrival processes. Thus, the tendency for unwanted performance to emerge can cause the function to produce too-late or too-close outputs.

This is slightly different from the conditions under which the ship sailed on the bay. Teamwork is not the main focus of this activity. Instead, system work focuses on functions related to the OOW and external factors, including environmental conditions (visibility level, tides, current, and wind) and traffic situations. Therefore, when sailing in the open sea, potential functional resonance may emerge between exogenous and endogenous variability related to the OOW's work. The functional upstream-downstream coupling between the OOW and

Helmsman may also contribute to a variability in performance; however, this is considered an infrequent event.

The OOW faces a demanding internal process when maneuvering the ship in encounter situations. This process involves collecting information about the target ship to make informed decisions and coordinating effectively with the Helmsman. Each decision made by the OOW during maneuvers must adhere to precise timing, ensuring that the work is conducted promptly and accurately while maintaining a safe distance from the target ship or other potential obstacles. Consequently, any undesired functional resonance among functions in this work could lead to the function being executed imprecisely, too late, or too close to the target, posing potential risks.

3.4.4 Current management of variability in performance

The analysis conducted here offers a clear presentation of how the observed ship operation manages performance variability. Significantly, the management of variability extends beyond the mere formulation of procedures or checklists. Instead, a deep understanding of the Officer's proactive initiative in navigating technical constraints provides invaluable insights for developing more responsive and supportive solutions for the system. In current ship operations, Officer adaptability can effectively dampen the variability of the natural environment, such as weather and sea conditions, as well as ship traffic situations. Additionally, collaborative teamwork and the utilization of technical instruments contribute to controlling individual performance variability. This dampening effect on variability yields several performance benefits, including enhanced patience, responsive instruction and feedback mechanisms, heightened situational awareness, and adaptive performance.

3.5 Discussion

This study provided some insight into the work-as-done point of view of learning safety in ship navigation. The core idea of Officer contribution to establishing safety in ship navigation has been recognized. In addition, the use of FRAM has revealed a greater understanding of the system resilience potency of everyday ship operations.

3.5.1 System resilience in Training-ship Operation from FRAM point of view

The potential of employing FRAM as a technique for assessing human and organizational factors in maritime transportation has been acknowledged and recommended [9]. The primary focus of this analysis is to emphasize the valuable insights that can be derived from the actual performance of ship officers, contributing beneficially to system resilience. The FRAM model and analysis explicitly showcase the bridge team's significant contribution to ensuring safe and effective ship movement. It highlights that Officer adaptability plays an essential role in maintaining safety, enabling Officers to be consistently responsive in dynamic situations during ship navigation. Qualitative observation supplements this analysis by presenting the working adjustments in a descriptive manner and providing empirical evidence to support it. Moreover, FRAM offers a systematic representation and a deeper explanation through the functional model.

Functional resonance stemming from the upstream-downstream relationship and endogenous and exogenous variability has been recognized as the source of performance variability when navigating the ship to arrive and depart from the berthing area. This underscores the imperative for collaborative efforts to achieve successful functions. The analysis reveals that the interdependency between certain functions in this scenario yields valuable information for the system to execute the wanted maneuvering actions. In contrast, it also illustrates how unwanted variability in the performance of one function can quickly propagate and lead to adverse outcomes for the entire system. This recognition of functional resonance emphasizes the critical need for a holistic understanding of the complex relationships between different functions to optimize system performance and resilience in maritime operations.

The complexity of navigating a ship in Osaka Bay has its own uniqueness compared with arrival and departure activities. In this situation, the system strongly relies on the OOW performance. The OOW has to consider multiple constraints, which often causes conflict in making manoeuvring decisions. This is particularly true for the safety and economic constraints introduced through the natural environment and traffic factors. In this case, the adaptability of the OOW is essential for maintaining resilience by prioritising higher-level goals [62]. However, while sailing in Osaka Bay, geographical aspects have little influence on the emerging amplifying effect of the OOW performance variability. The wider sea area provides valuable advantages for ship navigation in this situation. Consequently, it provides extra flexibility for the OOW’s work.

The FRAM model harnesses the potential of functional resonance by considering function couplings and various aspects, where the damping or amplifying effect can lead to performance variations. However, challenges arise in defining all potential upstream-downstream functional relationships for every aspect of a function. While the FRAM model aims for comprehensiveness and avoids oversimplification, applying it to model actual ship operations encounters several limitations. For instance, defining all six aspects for each function, especially the time aspect, proves challenging. Neither direct observation nor interviews can adequately capture this temporal dimension explicitly or implicitly. The sense of time for every function in ship operation is considered a part of the Officer's sensemaking and is inherently embedded in the Officer's related function, adding a layer of complexity to the modeling process.

3.5.2 The Essence of Adaptability and Flexibility of Ship Officer for Safety in Ship Navigation

This study effectively highlights the essential role of Officer adaptability and flexibility in establishing safety within the context of everyday ship navigation. A parallel observation aligns with findings from a study of traditional ship operations. The application of Safety-II principles in the context of traditional raft fishing reveals that continuous assessments and performance adjustments, grounded in the sensemaking of fishermen, contribute to the success of fishing expeditions [54]. In ship maneuvering, especially during encounter situations, the OOW's ability to manage a specific set of tasks concurrently becomes crucial. As illustrated in the third case in Table 3.1, the flexibility of ship officers in adjusting rules for specific ship encounter situations is deemed an adaptive advantage that warrants support. While rules are essential in the system, they may not be universally applicable to every situation. This is supported by research on the impact of maritime safety regulations on Norwegian coastal transport, which suggests that an abundance of rules and procedures may disrupt navigation activities [63].

As emphasized in the introduction, ship officers, as humans, should be viewed not only as a source of problems but as a key resource for managing the dynamics of sailing. It is critical to recognize that promoting human adaptability does not neglect the importance of technological development. Even in the three out of four degrees of autonomous ships defined by the IMO, the human operator is considered an integral component of the system [64]. Even in higher degrees of autonomy, complexity and uncertainty remain important matters [65]. Nevertheless, the skills and abilities of current officers must evolve to align with technological advancements and regulatory changes on the horizon. The development of knowledge and competencies are embedded not only in technology, procedures, and regulations, but also in seafarers as a holistic system [66]. Drawing lessons from the existing transportation system can furnish valuable insights for shaping a more advanced technological transportation landscape. Elevating the adaptive capabilities of ship officers, integrated into safety practices, holds the potential to enhance ship safety in future marine transportation [67]. Thus, finding a balance between technological development and human capacity is paramount for ensuring safety and availability in ship operations.

3.5.3 To monitor and learn, then respond and anticipate

It should be acknowledged that social components are the primary source of performance variability in the system. However, in this context, humans are considered a resource to keep the system flexible to cope with a degraded situation. The mean of the performance variability ensures that the performance demand can be fulfilled in a degraded situation by making local adjustments. It implies that system performance has to be variable. Subsequently, this leads to the idea that both success and failure are the consequence of working adjustments [24].

This is the first attempt to adopt a resilience engineering point of view in ship navigation based on an actual routine operation. This study raised a better understanding of how Officers create valuable performance for successful ship navigation. The four basic principles for system resilience contained in FRAM [68] have been recognised in ship-navigation activity through the analysis as follows:

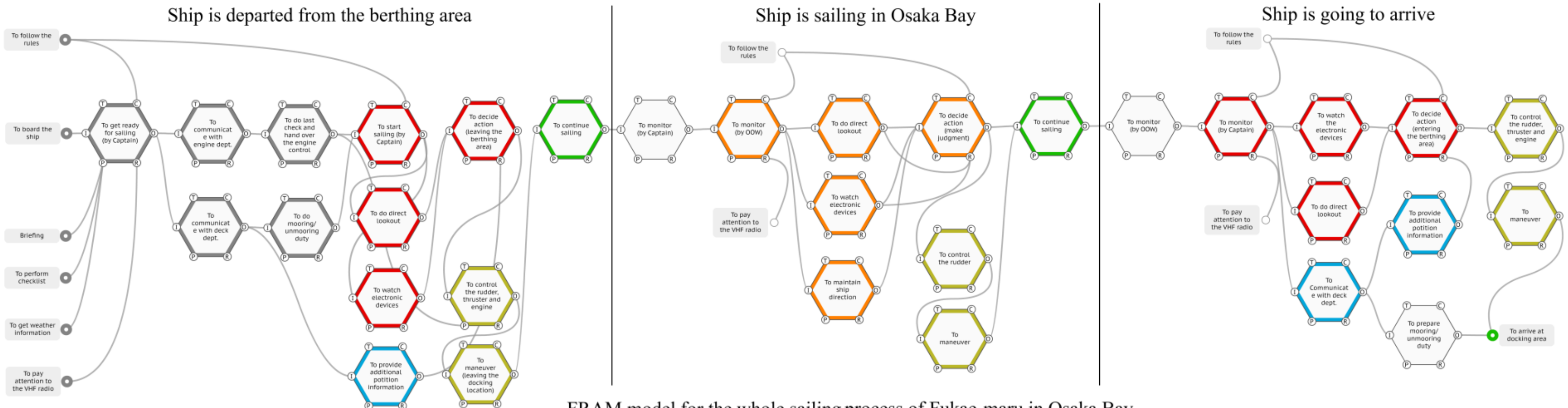
1. The potential to monitor: This is addressed in the function related to the lookout. The Officer knows what they are looking for in navigating the ship—the most important is ship traffic, especially the target ship, geographical situation, and environmental condition.
2. The potential to learn: Undoubtedly, an Officer's learning potential has a strong relationship with their experience. The dynamic functional model has presented how the Officer utilises their experience and what should be learned from the present situation. In addition, the local adjustment owing to the response process contributes to how Officers learn about the current situation. In return, this updated learning process also controls follow-up responses in the continuous manoeuvring process.
3. The potential to respond: The processed information generated from monitoring was used to activate this potential. The explicit representation of this potential can be observed in the dynamic model presented in Figure 3.4. The flexibility of the Officer is adequately highlighted, specifically for their ability to adapt to regular or irregular changes by producing proper action and adjusting the current mode of functioning.
4. The potential to anticipate: Foresight is created by combining experience and information from a current situation. Creating foresight in ship navigation often refers to expectations about traffic situations or the possibility of encountering other ships. In a more particular situation, such as a ship encounter, predicting other ships' intentions is essential for ship officers to create proper manoeuvring decisions. Navigation is a continuous process; therefore, anticipation initiatives will affect how Officers monitor and learn the situation. Equally, the recent ship-vicinity information will also update the anticipation initiative for a future event.

These resilience potentials identified in current ship operations underscore the importance of active human supervision within an advanced technology environment. However, this necessitates a parallel enhancement of internal-officer capacity. The resilience ability observed primarily involves adaptive goal prioritization to mitigate multiple goal conflicts that are commonplace in complex systems. Once, an Officer said, "*A change in passage plan is common, as well as arrival delays, as long as everything happens within reasonable limits. We hardly ever face a calm journey. Ship safety always comes first, without compromising our professionalism at work.*"

3.6 Chapter Conclusion

This chapter discusses the application of a resilience engineering perspective to assess safety in shipping operations. The primary focus involves analyzing the resilience capacity of ship officers' performance during the navigation of a training ship in a coastal area. It provides a fundamental understanding of actual work onboard at the system's functional level and how humans contribute to maintaining the system's normal functioning to meet operational demands. As a result, the functional model of shipping operations is introduced. In the specific context of shipping operations, a dynamic functional model of ship maneuvering is also presented in this study.

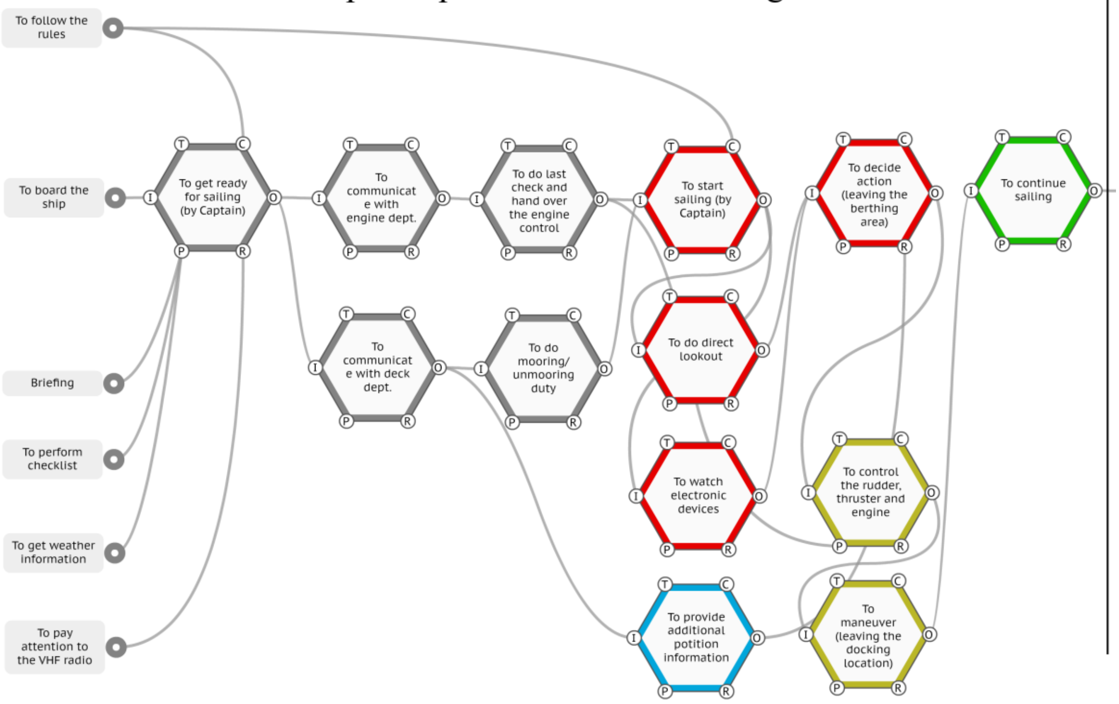
Appendix 1



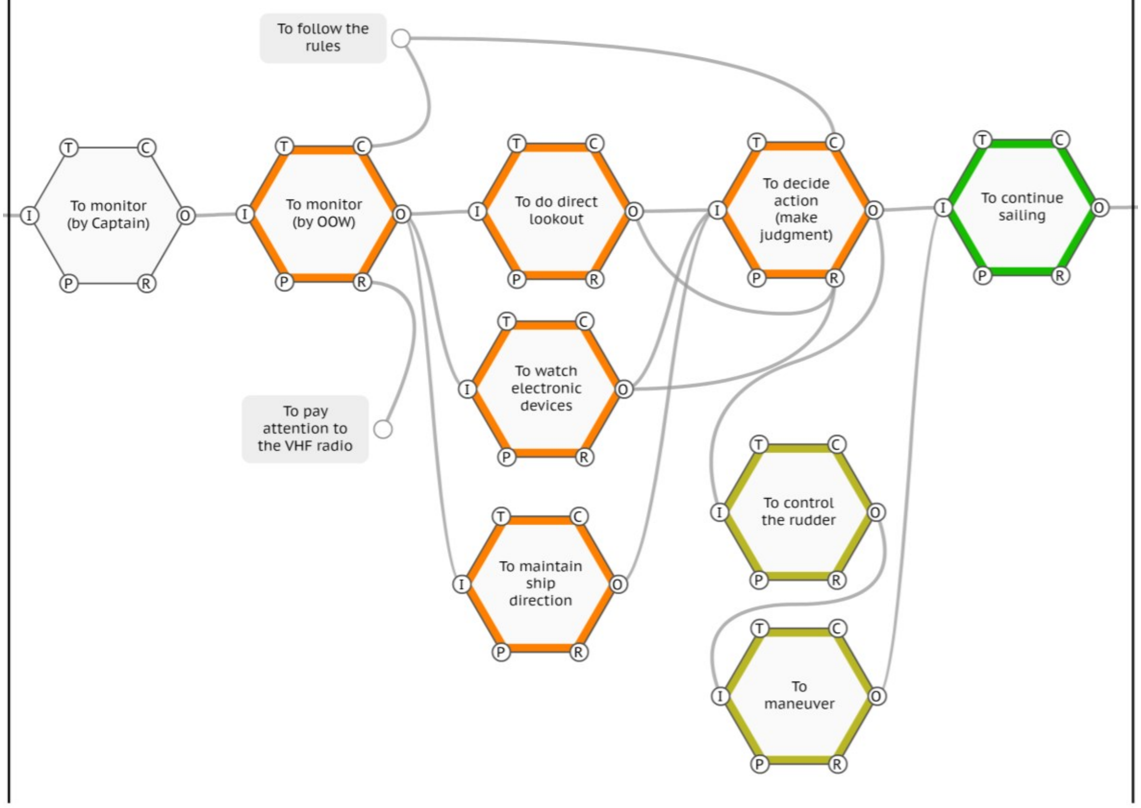
FRAM model for the whole sailing process of Fukae-maru in Osaka Bay

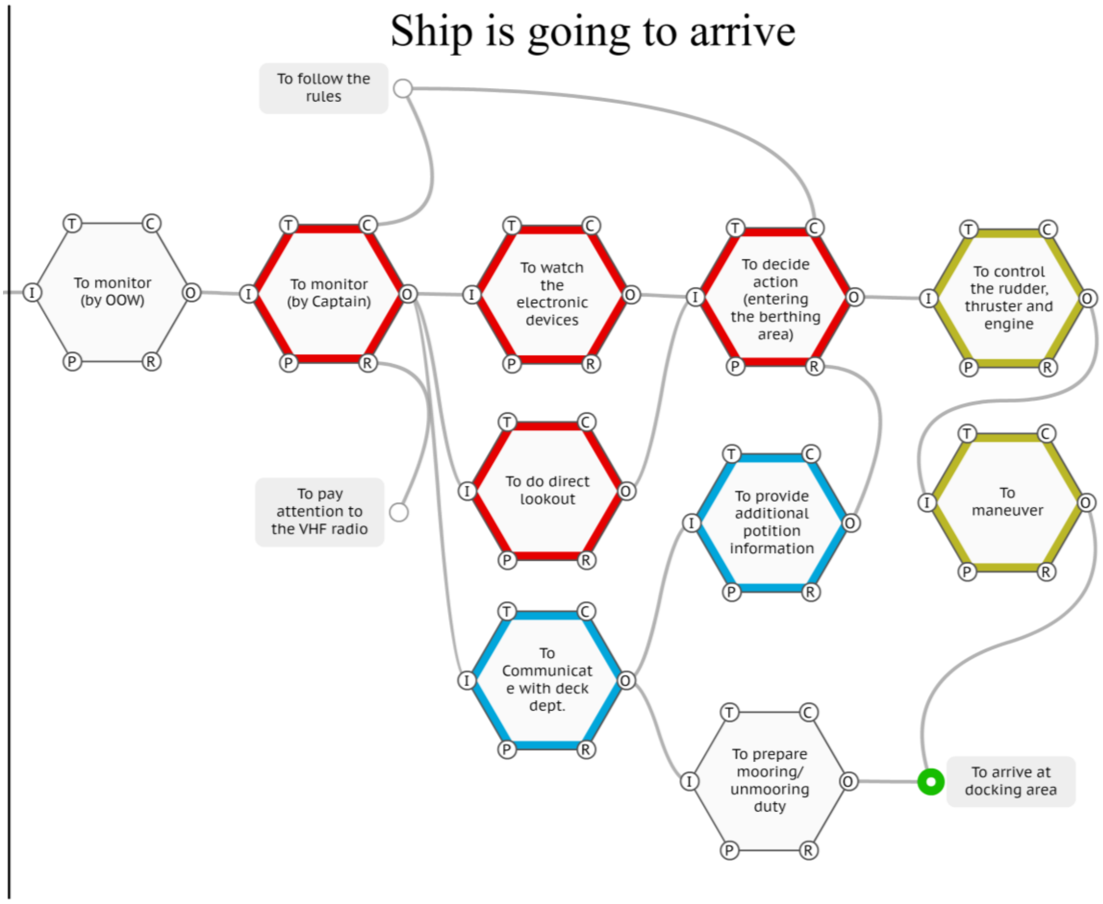
Detail of the overall model:

Ship is departed from the berthing area



Ship is sailing in Osaka Bay




Ship is going to arrive
To follow the rules
To monitor (by OOW)
To monitor (by Captain)
To watch the electronic devices
To decide action (entering the berthing area)
To control the rudder, thruster and engine
To do direct lookout
To pay attention to the VHF radio
To provide additional potition information
To maneuver
To Communicate with deck dept.
To prepare mooring/ unmooring duty
To arrive at docking area

Chapter 4
Assessing Ship Officer Flexibility in Challenging Ship-Ship Encounter: A Simulation Study

4.1 Introduction

The previous Chapter 3 discusses the fundamental basis of implementing resilience engineering in shipping operations through an analysis of the actual operation of training ships in coastal areas using FRAM. In this chapter, the relevance of applying resilience engineering in shipping operations is extended to a more specific context, namely, challenging ship-ship encounter situations. This study aims to further understand the adaptive and flexible capacities of officers to maintain their ship's normal functioning under unexpected encounter situations. Additionally, the cooperation between resilience engineering and a risk perspective is introduced to enrich and strengthen the analysis.

his study is attempted to address the core elements of successful ship maneuvering to establish safety in challenging navigation scenarios, with a specific focus on onboard work flexibility within the maneuvering process during unexpected encounters simulated in ship simulators. Learning from successful avoidance maneuvers in challenging encounters holds significant value for enhancing navigation safety [69]. This is critical because collision avoidance is one of the most dominant tasks in ship navigation. Ships operating under demanding workloads and unpredictable environmental conditions can greatly benefit from the adaptive performances of officers. The flexibility of onboard functions must prioritize safety, as achieving greater flexibility can enhance overall system safety [70].

To simulate an unexpected ship encounter, a ship simulator was employed. This simulator provides participants with a safe environment to test and express their performance limits in situations mimicking real-life scenarios [71]. The data analysis integrates the Safety-II concept and a risk perspective, offering a comprehensive understanding of ship officers' decision-making processes when navigating their ships safely under unexpected circumstances. The functional framework of everyday ship navigation activities based on Safety-II was adapted from a previous study. [61]. Risk value is expressed using an environmental stress (ES) model

[72], [73], and its applicability in analysing the subjective judgment of officers on watch (OOW) in manoeuvring decisions has been tested [74]. This work focuses on the relevance of integrating the traditional safety approach (risk concept) and Safety-II for assessing the variability performance of ship officers in difficult encounters.

4.2 Research Methodology

This sub-chapter contains the strategy and framework of the proposed method to assess the flexible and adaptable capacity of humans in relation to the safety of ship navigation under unexpected encounter events.

4.2.1 Data collection

The context of dangerous ship encounters was generated by simulating unusual ship encounters using a ship simulator. A dangerous encounter is difficult to encounter in actual field observations. This causes the simulation experiments to be considered more relevant for data collection. Seven participants, four professionals and three novices, were invited to participate in this simulation. They all have certificates of officers in charge of a navigational watch on ships of 500 gross tonnages or higher. The three novices have finished their formal education including the qualification in accordance with the provisions of STCW regulation II/1 (certificate of officers in charge of navigational watch on ships of 500 gross tonnages and more). However, they do not yet have professional experience as a company employee. The participant information is presented in Table 1. All simulations were performed with an approval from the participants, and the data were presented anonymously. Participants' onboard experiences varied from one year, 3–10 years, and > 10 years. The data were captured in the form of video and audio recordings. Furthermore, a structured interview was conducted to better understand every officer's decision while operating their ship.

The generated data type was selected to elucidate officers' decisions for overcoming the danger of ship collisions. In addition, structured interviews were conducted to understand the complex processes involved in manoeuvring a ship in unexpected situations [56]. A licenced officer was selected to provide a decision-making process that mimicked the actual field experience. The data collected in this research were limited to the ship encounter process. Limitations such as the difference in navigational aids equipped in this simulator were also applied.

Table 4.1. Participant Information.

Participant	Experience	Country of Origin
Participant A	>10 years	Japan
Participant B	2–5 years	Japan
Participant C	>10 years	Japan
Participant D	2–5 years	South Korea
Participant E	1 year	Japan
Participant F	1 year	South Korea
Participant G	1 year	South Korea

4.2.2 Experimental Design

This experiment, which included a challenging ship encounter event, prompted participants to engage in a simulation lasting approximately 15 minutes. At the onset of the simulation, no chart data or visual information beyond what is displayed on the simulator screen was provided to the participants. A verbal explanation was given as follows: "*The own ship is a bulk carrier with an overall length of 185 meters, currently half loaded. The engine status at the beginning of the scenario is standby engine full-ahead at 9 knots. The charted course is set as 'Var.' and the gyro course is set at 180º, representing a departure scenario from the port. The navigation task involves maneuvering the ship in a narrow area bordered by an island and peninsula, with fishing vessels positioned on both the port and starboard bows. Furthermore, red and green buoys, representing port and starboard hand marks, are visible. A red and white buoy, denoted as 'safe water marks,' is situated on the starboard side from the port hand mark. The ship's planned course involves altering to starboard toward this safe water mark after passing through the narrow area. However, participants are not initially able to see the mark at the beginning of the scenario. A ship is positioned in front of the own ship, moving in the same direction, serving as a guide to reach the destination. Simultaneously, another ship is situated behind the own ship, also moving in the same direction but at a faster pace.*"

Figure 4.1 provides an overview of the scenario, depicting the location of the own ship (highlighted in red), the first target (Target A denoted in blue), the second target (Target B indicated in green), and the trajectory of the targets. Target A's original trajectory is illustrated in blue, demonstrating highly inappropriate behavior. In a realistic ship encounter, Target A should follow the purple dashed line to appropriately enter the port. However, for the purpose of creating an unexpected situation for the participants, Target A was intentionally designed to-

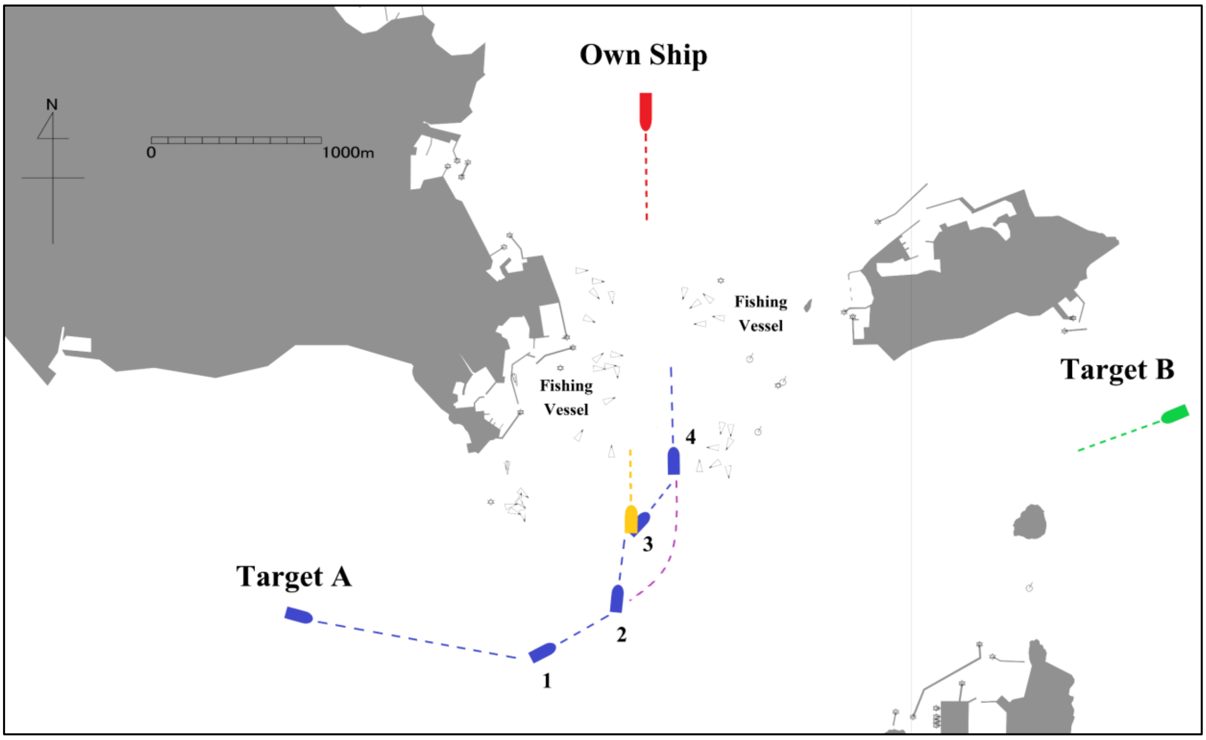


Figure 4.1. The overview of the location of the simulation, target ships, and own ship.

-pass over the east side of the shipping lane. Hence, after reaching the second and third points, Target A deliberately executed alternating rudder movements to the port and starboard side, simulating an attempt to collide with the participant's ship.

To streamline the scenario and avoid unnecessary maneuvers, adjustments were made to the behavior of Target A, taking into account potential participant reactions. Following the passage of the first target, participants maneuvered to avoid Target B, which was moving from northeast to southwest. Participants were encouraged to verbalize their thoughts during the simulation, allowing for the real-time capture of the cognitive processes involved. Additionally, a structured interview was conducted post-simulation to gather further insights into the decision-making processes employed by participants while operating their ships.

4.2.3 Combining risk concept and system resilience

Safety-II offers an alternative perspective by viewing safety as an emergent phenomenon arising from a complex socio-technical system rather than as a property of the system [39]. Humans have been acknowledged as a source of variability in complex sociotechnical systems. In this case, the system performance must be variable to deal with multiple constraints. This emphasises performance adjustment in everyday operations (Work-As-Done) for maintaining a system that works as intended [20]. Hence, the system can consistently achieve its goals, that is, operate safely.

The Functional Resonance Analysis Method (FRAM) is one of the leading methods that has been widely used for analysing safety based on the Safety-II perspective [40], [41]. FRAM analysis is focused on looking for *what goes right* in the system to make safety present in everyday operations. The system is expressed in a term called a function that describes the need for something to be done for a specific activity. It can be categorized into humans, technology, and organisations. There are four basic principles of FRAM, including the principle of equivalence of successes and failures, the approximate adjustment, the emergence phenomenon, and the functional resonance.

The ship handling simulation assessed in this study is designed to provide an understanding of ship officer working adjustment in difficult ship-ship encounter situations. The participant's action is expressed on the basis of its functional aspect derived from the FRAM idea. The four basic principles of FRAM are applied to categorize the function of the participant's action. As explained in the previous section, this exercise focuses on gathering participants' initiative to control the unexpected situation. In this case, the selected scenario seeks to present how work procedures, also known as Work-as-Imagine (WAI) can be very different from actual work (WAD) as a result of operator performance adjustment [20], [75].

Therefore, this simulation focused on the human aspect, in particular the OOW. The resolution for variability performance was achieved by characterizing it in terms of timing, precision, relative distance between the target and participant's ships, and the heading of the participant's ship. The application of the Safety-II concept was instrumental in comprehending the factors contributing to safe navigation, with a primary focus on performance adjustments that help overcome the dynamics of onboard work. The adaptability and flexibility of participants were observed, highlighting their capacity to navigate challenging encounters successfully. A more detailed exploration of function dependency is presented at a specific moment derived from the experiment.

4.2.4 The Environmental Stress (ES) Model with Safety-II Integration

This risk evaluation provides objective decision support for judging participants' decisions of navigating their ships, that is, the *ES* value is used to support the qualitative value expressed by Safety-II. The key aspect of this integration lies in recognizing the commonality between risk value and performance variability. For example, an accident in Safety-II is described as the inability of the system to reach the current circumstances due to the high number of performance variability from a phenomenon called functional resonance. It implies the difficulty to select the appropriate performance to cope with the situation which resulting the system producing unexpected output. In this case, this high-performance variability can be seen as linear with the risk level perceived by participants. This implies that better working adjustment leads to better control of performance variability, which is indicated by lower *ES* values. In addition, the parameters α and β in SJ_s predominantly consider the relative distance and ship heading, including the encounter situation, which is parallel to the solution provided for classifying the performance variability from a Safety-II point of view.

4.3 Narrative of the Simulation Result

The narrative of an actual event during the simulation is synthesized into a summary that contains the decisions made by all participants. This representation facilitates the identification of variations in each participant's decision-making process for navigating their ship. The chronological sequence of events is outlined below.

The first encounter event with Target A

A general explanation of initial event

00:00 – 04:30(note: *the time expressed in this study is based on the recorded video time scale)*

Following a brief observation of the current state of the ship's surroundings, participants exhibited two distinct strategies in their responses. Participants B, C, and D identified a cluster of fishing vessels on both the starboard and port sides ahead of the passage. In response, they adjusted their ship's course to 178°. On the other hand, participants A, D, E, and G believed there was sufficient space to navigate past the fishing vessels while maintaining their current course of 180°. At around 1:10* on the simulation time scale, all participants recognized the appearance of Target A on the starboard side of their ship, heading southeast (relative distance of ±1.8 NM). Notably, only participant D chose to utilize a VHF radio to confirm the intentions of the target. Participant D pointed out that relevant information about the target ship was limited due to the absence of navigation aids, particularly the automatic identification system (AIS). The communication lasted approximately ±3 minutes, encompassing a discussion on the agreement for the encounter. Furthermore, no specific actions were taken by the participants until 4:30*.

*04:31 – 06:00**

Target A was observed to change its direction for the first time to northeast at approximately 4:50*. Initially, all participants thought that Target A would slowly move north to enter the port and pass their ship's head safely. Consequently, they started to navigate their ship slowly to the southwest by ordering "185°/188°/starboard 5" towards the final destination. The timing of this action varied from 5:00 to 6:00 with a relative distance of ± 1 NM.

*06:01 – 07:40**

Later, at approximately 6:10*, Target A suddenly made a sharp turn to the north, prompting varied decisions from the participants in response to this unexpected behavior. Participants A, D, E, and G decided to maintain their southwest (starboard side) trajectory. Participant A, demonstrating proactive decision-making, promptly adjusted the order to "starboard 20" (t = 6:10*, R = ±1500 m). Participants E and G made a similar decision, albeit slightly later, at around 7:20*. Participant D communicated the meeting agreement and gradually navigated southwest. On the contrary, participants B (7:17*), C (7:12*), and F (7:40*) chose to cancel the previous order, steering their ships back to the original course by issuing "178°/180°," anticipating an encounter with Target A starboard-to-starboard. These disparate reactions were influenced by the initial decision to avoid the group of fishing vessels, leading to divergent positions relative to Target A between participants A, D, E, and G, and participants B, C, and F.

*07:41 – 08:10**

Between 7:20* and 8:10*, Target A continued its northward trajectory. For participants A, D, E, and G, this behavior created a situation where Target A appeared to be on a collision course. In response, at approximately 7:31* (R = ±960 m), participant A chose to use the ship's whistle to alert Target A. Around 8:11* (R = ±520 m), participant D placed a follow-up call to remind Target A about the meeting agreement. In contrast, participants E and G concentrated on navigating the ship while keeping their attention on Target A.

*08:11 – 09:30**

From the viewpoint of participants B, C, and F, the situation seemed relatively under control, anticipating a starboard-to-starboard encounter with Target A. However, around 8:25* (R =

±380 m), Target A was programmed to alter its course for the third time, heading northeast. This behavior change would have led to a potentially challenging situation for participants B, C, and F. As a result, Target A's movement was finely adjusted for these participants, making the encounter scenario reasonably appropriate, resembling a more realistic encounter. The first encounter concluded at approximately 9:30.

The second encounter event with Target B

A general explanation of event in the second encounter

The ship encounter is not a clean sequential event; rather, it is a messy continuous work with many simultaneously overlapping events. Stating a clear timeframe to differentiate between the first and second encounters is difficult. In general, the second encounter with Target B started at approximately 9:00–10:00*. However, strategies could have been previously arranged by participants. For example, the earliest decision, at about 6:50*, was made by participant D, who decided to use VHF radio (for the second time) to reach a meeting agreement with Target B. The follow-up action for this initial communication occurred 3 min after the encounter with Target A was completed.

The challenge that emerged in the second encounter primarily arose from the faster speed of Target B compared to the participant ship, coupled with Target B's position at the stern of the port side of the participant's ship. The participants approached this second event with different strategies, influenced by their experience in the first encounter. Participants B, C, and F encountered no specific issues. Considering their ship's current position, they monitored Target B's behavior and proceeded directly south until Target B safely passed the stern of their ship. Moreover, participant C emphasized the importance of being prepared on the VHF radio for communication, even in a seemingly safe situation with Target B, as a precaution in case of any sudden changes in Target B's movement.

09:31 to the rest of the scenario

The experience of the second encounter was slightly different for participants A, D, E, and G due to the impact of the first encounter, leading them to maintain a greater distance and larger crossing angle with Target B compared to participants B, C, and F. Participants A, D, and E performed for relatively similar actions, steering their ships slowly to the port side, maintaining a heading at approximately ±196º from 9:30* to 13:00*. Despite participant D's use of VHF communication, participants A and E chose not to engage in communication. Participant A acknowledged the challenging situation, emphasizing the need for sharp lookout and standby VHF communication in case Target B made any unexpected moves.

In contrast, participant G boldly decided to turn his ship sharply to the port side with an order of "port 20". He admitted to being unaware of the potential collision at that moment (9:40*, R = ±1160 m). Realizing the inadequacy of his initial decision around 12:00*, participant G attempted to adjust the situation with orders of "starboard 10" and "starboard 20", followed by another significant turn to the starboard side. He acknowledged the missed opportunity to confirm Target B's intentions through VHF radio. Although he believed that the "starboard 10" order could save his ship, it proved ineffective, leading to a collision between Target B and the stern end of participant G's ship.

4.4 Result Analysis based on ES and Safety-II

The primary descriptive functional process of this ship handling simulation is characterized by eight foreground functions and their dependencies, as outlined in Table 4.2. The qualitative functional process of the simulation results is illustrated in Figure 4.2, depicting the trajectory of the participant's ship. The system propagation is divided into two distinct groups, consisting of participants B, C, and F, and participants A, D, E, and G. This was done based on the relative similarity of decisions made by participants in navigating their ships

Table 4.2. Foreground function of ship encounter process.

No.	Foreground Function	Affecting the following functions
1	To monitor (by OOW)	<To do direct lookout>, <To watch electronic devices>, <To maintain ship direction>
2	To do direct lookout	<To decide action (make a judgment)>
3	To watch electronic devices	<To decide action (make a judgment)>
4	To maintain ship direction	<To decide action (make a judgment)>
5	To communicate	<To control the rudder/engine>
6	To decide action (make a judgment)	<To communicate>, <To control the rudder/engine>
7	To control the rudder/engine	<To manoeuvre>
8	To manoeuvre	<To monitor (by OOW)>

The simulation provided insights into local adjustments performed by participants to maintain normal operations in challenging ship-ship encounter situations. The study classified participant variability performance into four phenotypes: relative distance, timing, ship angle, and precision. In addition, the ES value was incorporated to offer a more comprehensive analysis of participants' decision-making, particularly in terms of collision risk. Unfortunately, the simulation did not clearly reveal a connection between the functional aspects associated with Officers on Watch (OOW) and Helmsmen. This lack of recognition was emphasized by statements from six to seven participants who acknowledged the importance of teamwork for navigation but did not explicitly consider collaboration with Helmsmen in their decision-making processes.

This simulation analyses participant decisions on an individual basis. Due to this approach, the limited number of participants does not significantly impact the results. In Addition, as mentioned in the previous chapter, no formal statistical analysis is conducted to draw generalizable conclusions from this study. However, in this new method, the focus on examining successful encounter strategies can still contribute to a deeper understanding of safer ship navigation. This is further enhanced by incorporating the concept of risk into the FRAM analysis. This inclusion of risk adds a layer of objectivity to the traditionally qualitative FRAM approach, strengthening the validity of the analysis results.

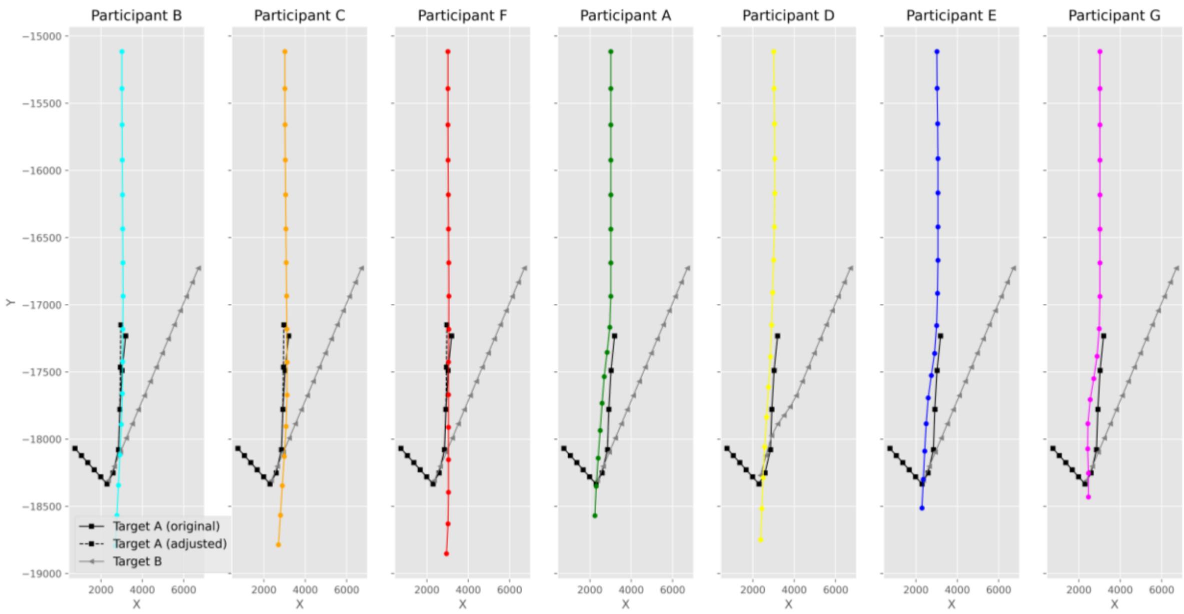


Figure 4.2. The trajectory of the “own ship” operated by the participant.

4.4.1 The encounter event with Target A

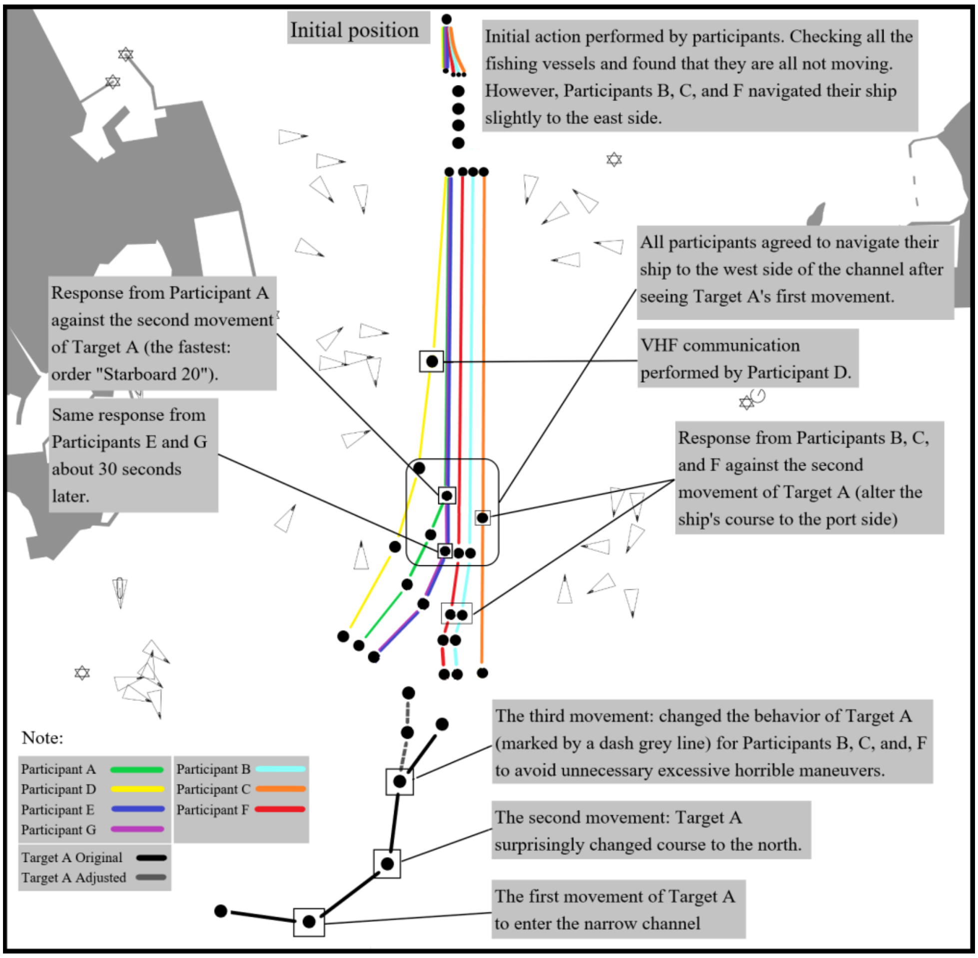


Figure 4.3. Summary of participants' actions during the first encounter with Target A.

Figure 4.3 provides a summary of participant actions, revealing that participants formulated their initial navigation strategy at the simulation's onset. A robust dependency is observed between functions such as <To monitor (by OOW)>, <To do direct lookout>, <To watch electronic devices>, and <To maintain ship direction>, which collectively contribute to the process of vicinity observation for learning and monitoring. In subsequent cycles, the outcomes of these functions influenced the output strategy of the <To decide action (make a judgment)> function, determining the response to address the situation. However, the simulation identified that identical input information from the monitoring and learning functions for the <To decide action (make a judgment)> function could yield different system outputs. This suggests the presence of a concealed background function influencing the internal variability performance of <To decide action (make a judgment)>. For instance, in the scenario involving the group of fishing vessels, the simulation detected distinct personal preferences in control aspects related to safe passing distance and specific resource aspects. Notably, -

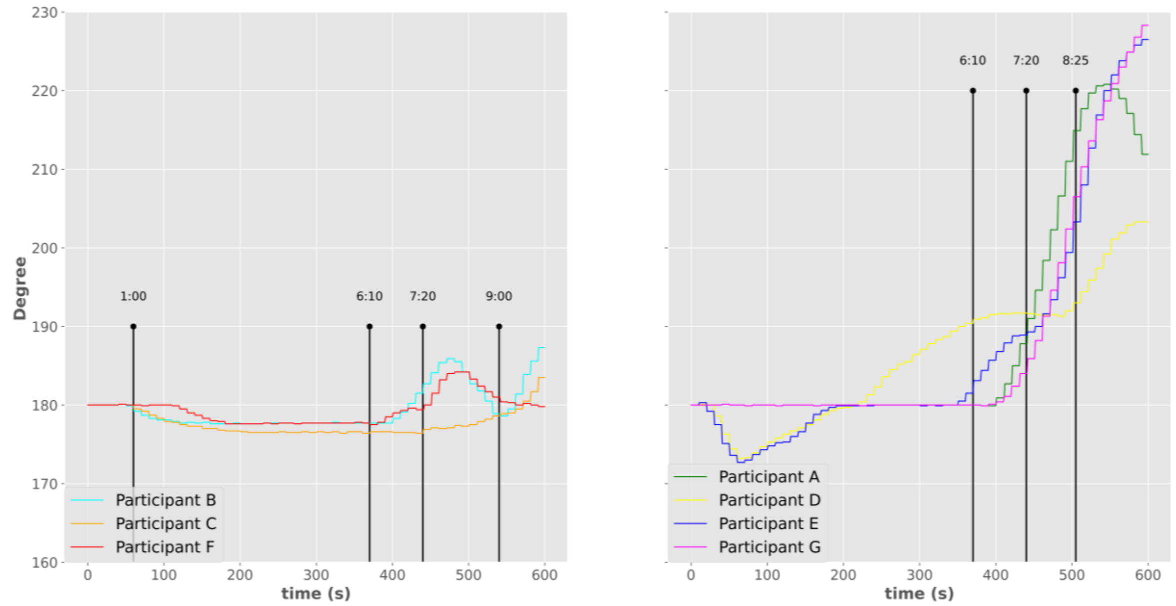


Figure 4.4. The change of ship’s heading with respect to the time of the first encounter event.

-participant D employed VHF radio due to the lack of information about the target ship. Figure 4.4 illustrates the differences in participants' decisions concerning changes in the ship's angle over time. However, this contrast cannot be represented through the ES since the fishing vessel remained stationary in the simulation.

The simulation highlighted a distinct response to Target A's behavior later in the scenario, with a specific timestamp in Figure 4.4 illustrating variability in participants' performance based on changes in the ship's heading. Notably, the function <To decide action (make a judgment)> exhibited a clear potential for high variability performance. Participants A, D, E, and G demonstrated relatively identical actions, but participant A displayed quicker reactions compared to participants E and G. Participant D adhered to the meeting agreement. Moreover, participant A demonstrated advanced actions by promptly using the ship's whistle upon detecting Target A's unusual movement, showcasing better control in performance variability, particularly in terms of timing, precision, and the ship's heading. This observation aligns with the ES values depicted in Figure 4.5, where participants A and D exhibited lower values compared to participants E and G, although with a small gap. Furthermore, Figure 4.6 illustrates a notable difference, with participants A and D maintaining a greater distance from Target A during the critical 60-second period leading up to the encounter.

The identical responses from participants B, C, and F, in contrast to participants A, D, E, and G, can be attributed to the differences in the position they created for Target A. An additional calculation was conducted for participants B, C, and F, taking into account both the adjusted and designed behaviors of Target A. From their perspective, participants B, C, and F seemingly had no viable way to counter the third movement of Target A, especially when it made a sudden and striking movement at a relative distance of ±150 m. This situation emphasizes the amplifying effect of functional resonance, leading to an irregularly increased number of performance variabilities and making it more challenging to select an appropriate response, particularly in terms of maintaining a safe distance, which was already deemed "too close." A more in-depth analysis of this situation can be observed by comparing the ES value and relative distance in Figure 4.7. In the designed behavior, during the last 60 seconds of the encounter, the ES value reached a maximum of 1000 for all three participants. Particularly for participants B and F, the closest distance to Target A was nearly 0 m, indicating that the target struck the participant’s ship right in the middle.

In response to the issues identified, adjustments were implemented in the simulation by modifying the behavior of Target A to better align with the appropriateness of its actions in an actual ship encounter. All participants recognized the unusual movement of Target A at approximately 06:00* and made corresponding adjustments to their performance. This indicates that participants were adept at detecting early signals of high-performance variability. Participants B, C, and F exhibited substantial performance adjustments in this more realistic scenario. A more thorough evaluation reveals that the maximum ES value persisted for only 10 seconds for participants B and F, while participant C achieved even better performance, with the ES value dropping significantly below 500.

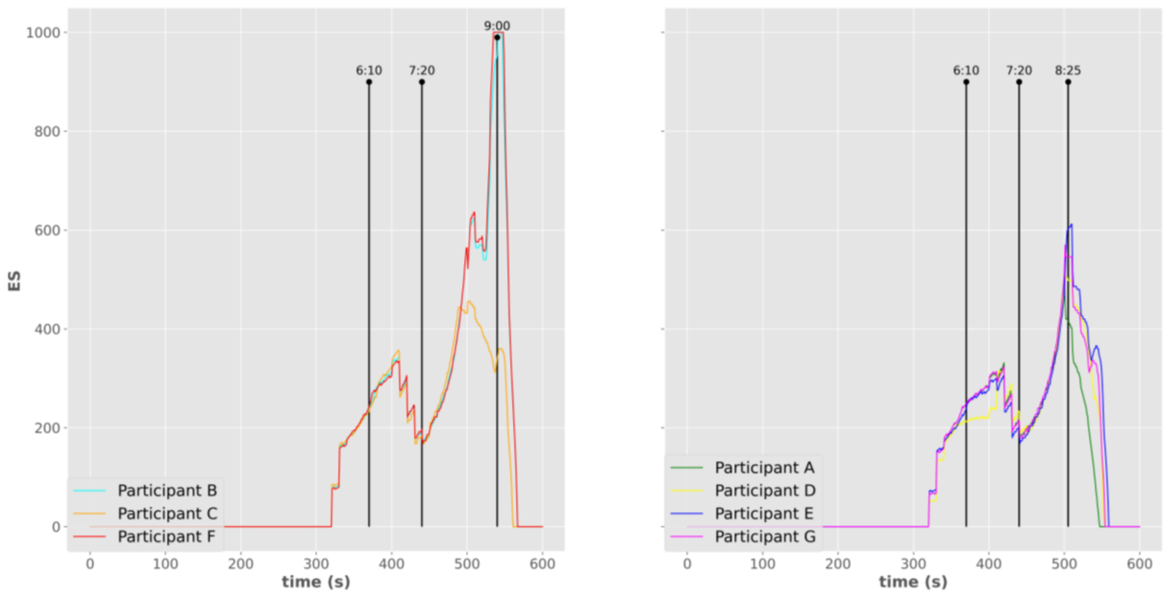


Figure 4.5. The change of ES with respect to the time of the first encounter event.

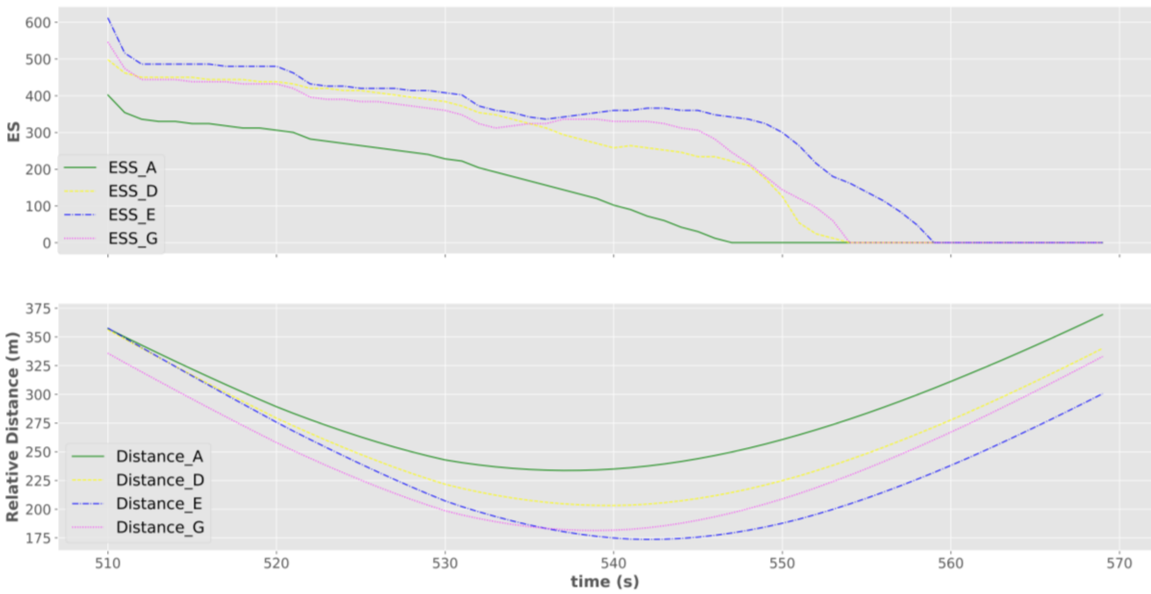


Figure 4.6. The ES and relative distance in a critical 60 seconds of the first encounter event of participants A, D, E, and G.

The simulation was designed with the expectation of capturing unique adjustments if such situations were to occur. However, those specific adjustments were not observed during the simulation. The subsequent interviews shed light on the participants' perspectives, with participants B, C, and F characterizing the vague movement of Target B as resembling a "suicidal" intent. Participant F cited concerns about disturbing communication in a congested sailing area as a reason for not considering the use of VHF radio in this scenario. Participant B emphasized the importance of Target A understanding the intended starboard-to-starboard meeting, and expressed a lack of consideration for using the ship's whistle in response to the third movement due to a lack of experience.

In summary, the decisions made by participants A, D, E, and G were generally more flexible than those of participants B, C, and F in the first encounter. This flexibility is reflected in the small gap in the ES value for participants A, D, E, and G. Participants E and G were late to recognize the slow rate of turn in their first action (6:10*) against Target A compared to participant A. On the other hand, a slight difference in ship heading between participants C with participants B and F resulted in a large difference in the ES value. This suggests that variability performance is more sensitive, especially concerning time and ship angle, in the case of participants B, C, and F, where the amplifying effect of function dependency easily affects the system.

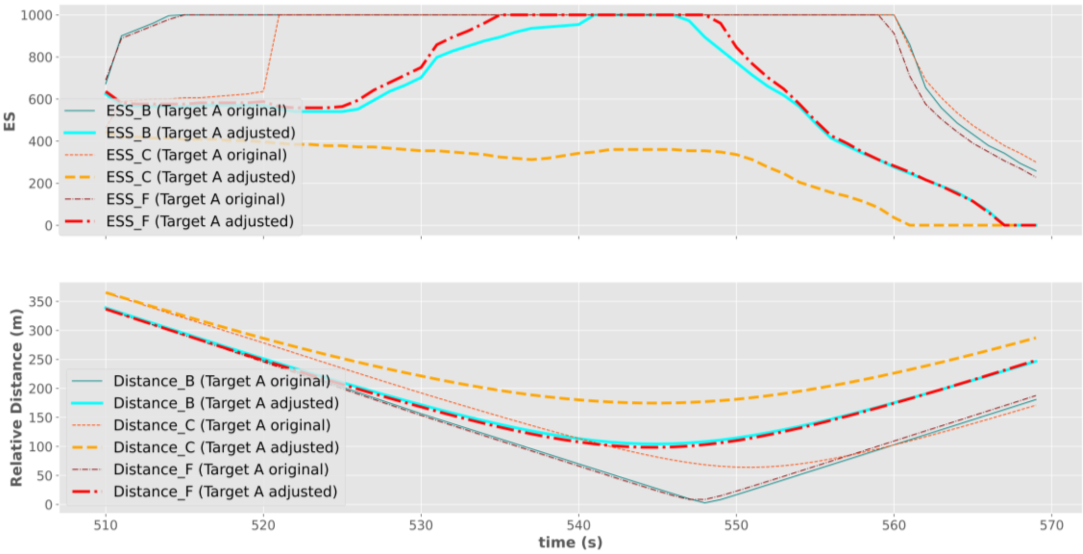


Figure 4.7. The ES and relative distance in a critical 60 s of the first encounter of participants B, C, and F.

4.4.2 The encounter event with Target B

During the second encounter, an unwanted working adjustment came to light, with Figure 4.8 providing a comprehensive summary of the participant's actions. In particular, participants A, D, E, and G exhibited distinct behaviors, with participant G standing out for taking the longest time to initiate the action.

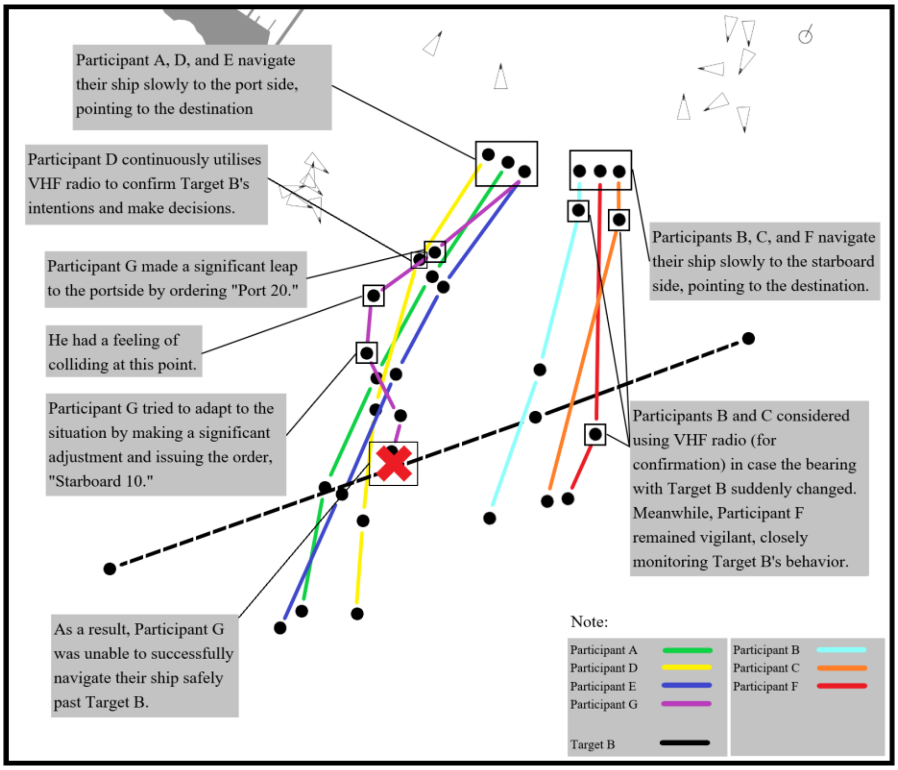


Figure 4.8. Summary of participants' actions during the second encounter with Targ et B.

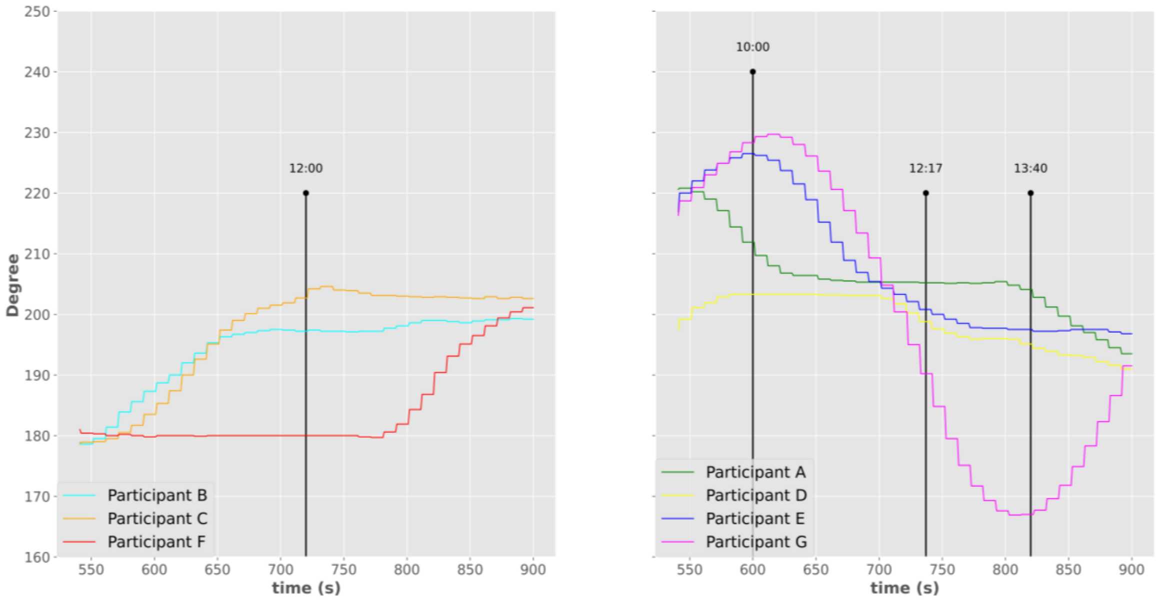


Figure 4.9. The change of ship's heading with respect to the time of the second encounter event.

This participant performed a swift turn against Target B in terms of timing and the ship's angle, as illustrated in Figure 4.9. An early indication of high variability performance from <To do direct lookout> surfaced around 9:40*, likely serving as the primary instigator of the amplifying effect between <To do direct lookout> and <To decide action (make a judgment)>. This interaction led to an undesirable outcome, specifically the issuance of the "port 20" order.

The final adjustment, executed at 12:17*, was deemed "too late," resulting in a system malfunction and an inability to sustain normal operations. The consequential stress experienced by participant G is reflected in the ES results presented in Figure 4.10, where the stress value rapidly increased to 1000 points after the issuance of the "port 20" order. This sequence of events underscores the critical role of timely actions and the intricate interaction between different elements in maintaining effective system functioning.

Furthermore, participant E's situation highlighted the boundary between acceptable and unacceptable functional outputs. In this case, participant E demonstrated better adjustments compared to participant G, particularly in relation to the heading decision. The examination of the ES and distance covered by participant E, as illustrated in Figure 4.11, reveals that a slight delay in timing or a larger heading adjustment could have resulted in a collision for participant E. Even though the case is specific to the situation presented, these two performances exemplify how to detect the signal of functional resonance and its usefulness in identifying the potency of abnormal amplitude in variability performance.

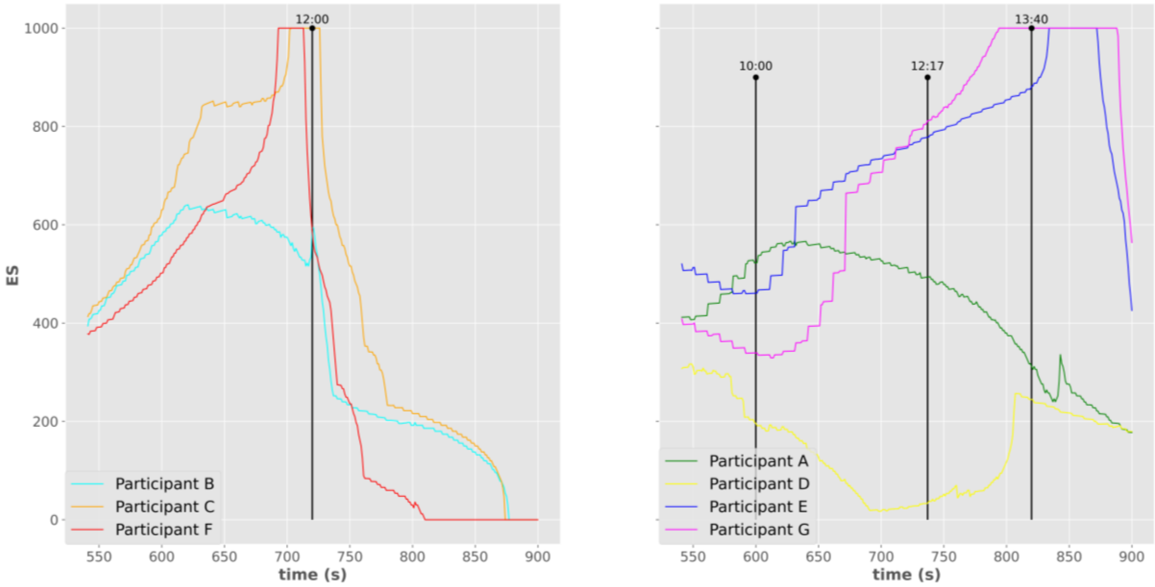


Figure 4.10. The change of ES with respect to the time of the second encounter event.

It is also important to note that participant E's emotional response further expresses the gravity of the situation. Immediately after Target B safely passed his stern, participant E expressed his feelings with the word “kowai,” signifying "so scary" in Japanese. This emotional reaction adds a human dimension to the assessment, emphasizing the genuine apprehension and potential consequences associated with navigating the boundary between acceptable and unacceptable system performance.

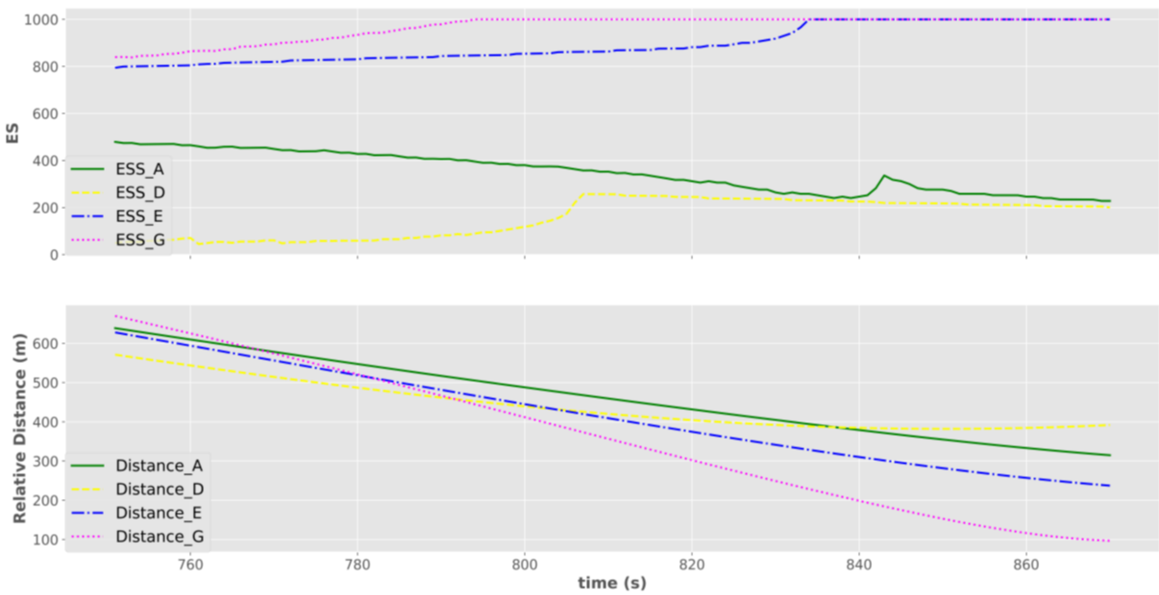


Figure 4.11. The ES and relative distance in a critical 120 s of 2nd encounter of participants A, D, E, and G.

In contrast, the second encounter occurred faster for participants B, C, and F. Figure 4.12 illustrates the high ES values perceived by participants C and F. However, this high ES value was observed to last for only approximately 30 seconds, similar to the first encounter. This indicates a short distance managed by the participants as Target B passes the stern of their ships. Participants B, C, and F argued that, based on the current headings of their ship and Target B, they were confident that their ship could pass the intersection point between the two headings' projections before Target B. Figure 4.9 further illustrates that participants B and C adopted the same maneuvering strategy but differed from participant F. This strategy was influenced by the need to navigate their ship to the final destination rather than the need to avoid Target B. Their relatively similar positions at the end of the simulation, as shown in Figure 4.9, reflect this strategy.

Participant D's advantageous use of VHF radio communication is evident from the low ES values in both encounters. In the case of participant G, if <To decide action (make a judgment)> could activate and establish a link with <To communicate> at 12:17* as an adjustment of the previous action, it might have propagated the system to produce the desired outcome. Participant G considered using the whistle or VHF radio but decided against it, thinking the situation differed from an actual ship encounter. While there are no explicit rules to judge a good or bad situation for the use of VHF radio, participant D's overuse of VHF radio could potentially lead to irregularly high variable performance in actual ship encounters.

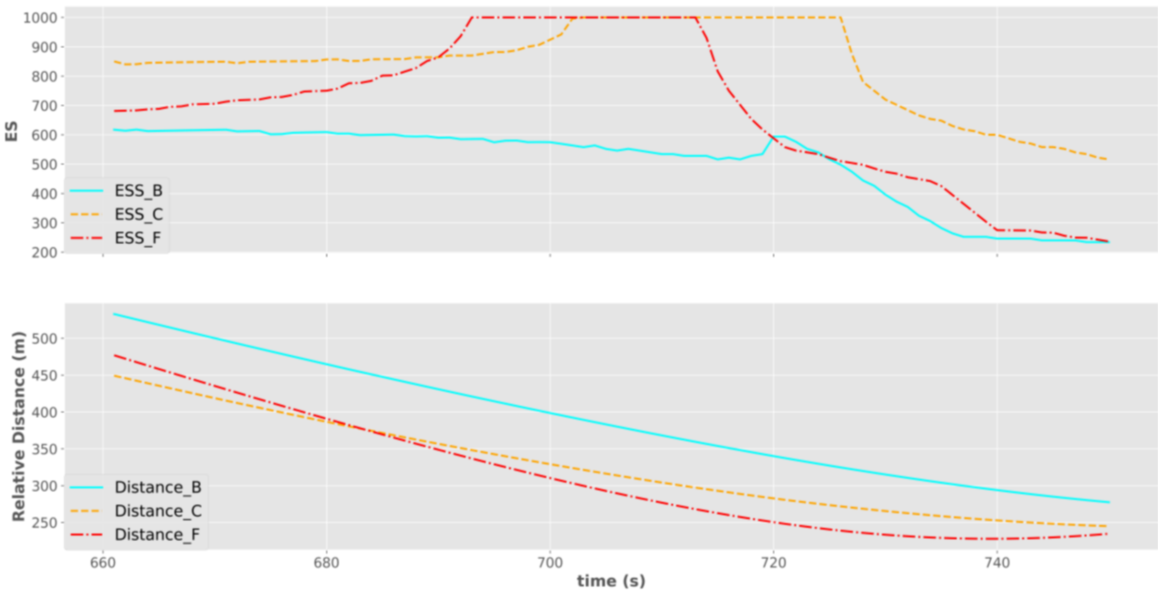


Figure 4.12. The ES and relative distance in a critical 90 s of the 2nd encounter of participants B, C, and F.

4.5 Discussion

This study acknowledges several limitations, including the absence of natural disturbances, defined time constraints, limited social interactions, and working routines, which create distinctions between simulated and actual working environments. However, unexpected situations are infrequent in real-world systems, potentially involving various ineffable problems. Previous studies on shuttle tanker operations have highlighted the reflective nature of simulator training, allowing officers to critically assess both successful and unsuccessful aspects of their sessions. [76]. The spirit presented in this work is on comprehending ship safety, with a learning process initiated by devising solutions where the motivation and initiative of ship officers are regarded as valuable resources for system adaptability and flexibility. Furthermore, technological developments can always exploit human abilities through great human-autonomy collaboration.

Successful maneuvering is defined as the ability of an OOW to overcome obstacles and safely guide the ship to its destination. This study identifies success factors in ship navigation, utilizing the Safety-II concept and a risk perspective, providing a robust framework for assessing the complexity of ship navigation. As suggested by Aven [43], integrating the risk concept enhances decision support and understanding in dealing with intractable and complex systems. The Work-As-Done (WAD) analysis of onboard operations, starting from determining its functional level, unveils a unique system propagation process for adapting to situations, particularly those related to ship traffic. The continuous and repetitive activation of functions has been shown to increase functional resonance among them, emphasizing the critical role of a ship officer's flexibility in ensuring system performance and safety. This is consistent with the concept of resilience as a graceful extensibility [77], which views the need to extend the system's adaptive capacity to face unexpected events [78]. This study reveals three crucial elements for a successful strategy in achieving safe ship navigation by ship officers:

The balance between safe and efficient manoeuvring strategy

The decision-making process in ship manoeuvring involves more than just avoiding obstacles; it involves a complex interaction of factors such as the need for swift transportation, cost-effective operation, and maintaining a high level of safety. A trade-off exists among these factors, and determining the most critical factor at any given moment is essential. This prioritization is dynamic and varies across different situations and over time. Despite these dynamics, the system must consistently formulate manoeuvring strategies that are both safe and effective. For the ship officer, tasked with making these decisions, achieving a balance between these factors in each situation becomes a challenging issue. This is in line with the efficiency-thoroughness trade-off (ETTO) principle, which states the need to make trade-offs between efficiency and thoroughness to maintain everyday operations [37]. When there is a heightened demand for safety, there may be a reduction in efficiency to meet safety goals. On the other hand, when productivity or performance is the priority, there may be a reduction in thoroughness to achieve performance objectives. This delicate balance reflects the simultaneous need to respond to immediate demands and anticipate future scenarios.

The early response

This short simulation revealed the different working adjustments made by each participant in maneuvering the ship. The initial navigation strategy changed multiple times in response to the continually changing traffic situations. Regarding maneuvering actions, participants exhibited distinct preferences regarding when and where these actions should be executed. Early responses, initiated promptly after recognizing the inappropriate behavior of the target ship, were deemed crucial for enhancing navigation safety. This approach involved maintaining a sharp lookout and making precise judgments about the target's behavior. It was recognized that a more experienced participants were observed to trigger these early responses more readily. The concept of learning potency, which involves understanding current situations to formulate responses and anticipate future events, is sharpened through experience. It goes beyond merely reusing past experiences, emphasizing the application of relevant experience to the present context. A high level of system resilience is expressed by the ability to adapt to unplanned events in which the perturbation can be anticipated, controlled, and managed [79], [80]. Ensuring that the advanced responses of more experienced seafarers are effectively passed on to the younger generation emerges as a critical consideration. This strategic knowledge transfer aims to accelerate the learning abilities of the younger generation, equipping them with the skills needed to navigate complex and dynamic maritime scenarios.

Proper use of the ship's whistle and VHF radio

Communication plays a crucial role in ship navigation, and while its importance for maintaining safety is undeniable, specifying the precise and optimal use of communication aids can be challenging. In this simulation, an effective strategy involving the use of VHF radio was demonstrated. Participant D exhibited a useful variability in the communication function by activating it in advance, showcasing a proactive approach. Participants A and B also demonstrated wise consideration of utilizing VHF radio during the second encounter. The simulation highlighted that incomplete information or vague target movements could serve as signals for activating the communication function.

For effective bridge-to-bridge communication, it is imperative to establish agreements that incorporate COLREG, ensuring a clear understanding of responsibilities by all parties involved [81]. However, the simulation also revealed the potential drawback of overusing VHF radio, as seen with participant D. Repetitive communication through VHF radio has the potential to induce unnecessary actions or miscommunication, leading to an abnormality in performance variability. This aligns with the concept of increasing mental workload, especially with the high concentration required for VHF radio communication [82]. Furthermore, the simulation presented a noteworthy performance adjustment involving the use of the ship's whistle. The fact that only one participant utilized the whistle suggests room for improvement in the utilization of this communication tool more effectively.

Safety-II has found alignment with various concepts, such as work engagement [83] and individual latent error detection (I-LED) [84], to address broader safety issues within routine operations that might not have been adequately addressed by organizations while formulating safety strategies. Aside from the diminishing supply of seafarers, human error remains a significant factor motivating initiatives in the development of MASS. However, even as these initiatives aim to reduce human involvement, humans are still integral to three out of four aspects of the IMO's agenda for autonomous ships. Moreover, many problems remain to be discussed, especially those related to the rules required for operating MASS [85]. While the necessity of seamanship may be debated, it is generally acknowledged. Therefore, understanding the work of professional officers remains critical, especially if the system continues to rely on human involvement.

This study provides specific results from a particular scenario, and caution should be exercised in generalizing these findings to every situation. However, commitment to appreciating human performance [67] is a guiding principle. Human performance is inherently variable, contributing to the flexibility and resilience of the system. Technological advancements must be accompanied by an acceleration in human operator skills and knowledge. Achieving harmony in the collaboration between humans and autonomous systems represents the future of ship navigation.

4.6 Chapter Conclusion

This chapter presents a deeper understanding of officers' adaptive and flexible capabilities in the specific context of challenging ship-ship encounter events. The unique ship-handling simulation scenario and analysis showcase different participant performances, with performance variability leading to various strategies by each participant. This indicates the potential for improving system flexibility and adaptability based on useful maneuvering strategies identified in the simulation. Furthermore, the combined method of FRAM and ES model has shown promise as a tool for assessing resilience potency in shipping operations. The ES can enhance and enrich FRAM analysis by providing objective measurements.

Chapter 5
Extended Approach of Ship Officer Performance Based on FRAM-DBN Analysis

5.1 Introduction

In the previous Chapter 4, an analysis of the particular context of shipping operations, specifically challenging ship-ship encounter situations, has been discussed. Additionally, the combined method of FRAM and ES model was introduced for a more comprehensive analysis. While the ES provides objective support for FRAM through the ES score, it does not directly express performance variability. Moreover, the critical point emphasized in that method combination is the potency to incorporate resilience engineering with the risk concept. As a continuation, this chapter proposes a separate combination that strongly highlights the presentation of performance variability in a quantitative manner.

The elaboration of ship officer performance variability analysis through temporal model using Dynamic Bayesian Network (DBN) is presented. While the ES Model provides valuable support for the FRAM analysis of officer decisions in extreme ship-ship encounter events, the FRAM-DBN combination aims to directly represent the officer's performance. DBN is an extended version of the Bayesian Network (BN). It is a type of probabilistic graphical model that can be used to model complex, dynamic systems over time. BN has been widely applied in the maritime industry, especially to predict the probability of ship accidents [86]–[88]. One of the advantages of DBN is this method can handle temporal dependencies and allow for the modeling of time-varying influences on system behavior. The basic idea of this quantitative expression is to model the discrete probabilistic dependencies between functions at each point in time, and then to propagate these dependencies over time to express a dynamic change in the system.

The application of FRAM in this study is to identify the functional basis of ship maneuvering activity and provide a systematic expression of it through functions and potential couplings. It provides an explicit understanding of the system's functionality in the form of FRAM model but lacks in function's performance representation. One solution that can be applied is cooperating with the method of quantitative analysis. Some available studies have existed regarding this matter, such as the application of Monte Carlo evolution [89] and modified Fuzzy FRAM-CREAM with cellular automata simulation [90].

Therefore, in addition to employing the Functional Resonance Analysis Method (FRAM), this study incorporates a Dynamic Bayesian Network (DBN) for mathematical modelling. The chosen case study, drawn from a ship handling simulation presented in Chapter 4, serves as the basis information for the analysis. The integration of FRAM and DBN in this study aims to demonstrate and construct a comprehensive model of ship officer variability performance. This model offers insights into how shifts in officer performance over time impact the overall system output. The selection of this specific case facilitates real-time segmentation of each decision initiative and provides tangible performance evidence for DBN analysis. This straightforward analysis is designed to illustrate the expected outcomes of performance adjustments, demonstrating how normal performance can be disrupted and lead to undesired results. In summary, the focus is on addressing the essence of human performance in establishing an adaptive system, necessitating the development of strategies to enhance resilience at a higher level.

5.2 Research Methodology

This section explains the method applied in this chapter. First is the qualitative analysis using FRAM and building the FRAM model. Second is integrating the FRAM analysis with quantitative analysis based on DBN. In addition to that method integration, the control model from Cognitive Reliability and Error Analysis Method (CREAM) has been brought to provide characteristics for FRAM function. This characteristic includes strategic, tactical, opportunistic, and scrambled.

5.2.1 FRAM as a retrospective analysis

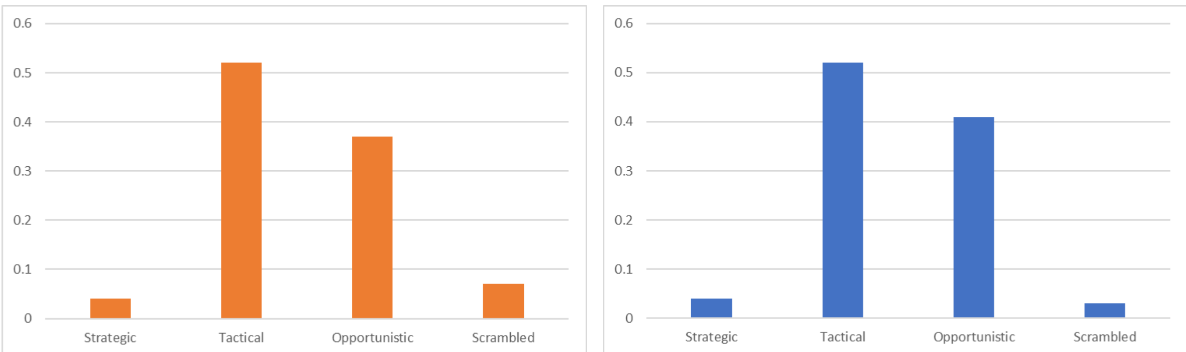
The purpose of FRAM as a retrospective analysis is to understand how the system should have functioned to successfully achieve the desired goal—in this case, to successfully avoid the target ship. Moreover, in the given accident case, FRAM explained how the variability of functions, either alone or in combination, prevented that from happening. Typically, this is the variability that existed in the situation being analyzed, but it could also be the variability that might possibly exist under other conditions.

It is worth noting that a FRAM model describes the potential couplings among functions, not an actual sequence of events. Therefore, the model presented in Chapter 3 can be modified based on the accident case being assessed in this chapter. This instantiation serves as a factual sequence of how potential variability becomes actual variability in a given situation. In this case, the actual coupling among functions is also presented. Therefore, FRAM is able to identify the potency of functional resonance, wherein the 'abnormal' (too high or too low) performance variability developed and caused such an unintended event to happen

5.2.2 Officer performance quantitative representation using DBN

In this chapter, DBN is used to provide a quantitative expression of the qualitative analysis that has been provided by FRAM. To integrate the FRAM with DBN, it is necessary to define a characteristic for each function to generate a conditional probability table (CPT). Moreover, the control mode expressed in CREAM [91] is selected to generally characterize the FRAM function. It consists of strategic, tactical, opportunistic, and scrambled. Strategic control mode involves considering the global context, using a wider time horizon and higher-level goals, leading to more efficient and robust performance, and planning based on the functional dependencies between task steps. Tactical control mode involves performance based on limited planning, ad hoc needs, and frequently used procedures that may seem rule-based due to context or performance conditions. Opportunistic control mode entails determining the next action based on salient features of the current context, frequently resulting in functional fixation, driven by perceptually dominant features of the interface or frequently used, familiar heuristics. Scrambled control mode involves unpredictable decision-making without much thought, often occurring during high task demands or in unfamiliar, rapidly changing situations that lead to a loss of situational awareness, potentially culminating in momentary panic. Hence, the temporal relationship of the function's mode in which the explicit representation of changes in performance over time is presented through Bayesian thinking.

The determination of control mode in CREAM typically involves evaluating a specific criterion related to a task. However, this study adopts an approach where the determination of the control mode is represented as a discrete probability distribution. Figure 5.1 illustrates an example of the discrete probability distribution for the control model within a given context of a common performance condition. Building on this concept, it is possible to use this idea to determine the CPT for the initial condition of DBN. Consequently, the estimation of the CPT for the FRAM function in a maneuvering event is formulated by combining the discrete probability of the CREAM control mode with an adjustment based on the common knowledge of officer performance in ship navigation.



(a) (b)

Figure 5.1. Discrete probability distribution of control mode based on (a) CPC's output variability [92] and (b) probabilistic approach [93] (adapted from [94]).

5.2.3 Case study

A case from ship-handling simulation presented in Chapter 4 has been chosen to provide a factual story of ship maneuvering events. The chosen simulation contains an accident event in which the action taken by the participant in each time slice is recognized. A deeper understanding of participant's decisions has also been elaborated through structured interviews. The participant is a licensed Officer with one experience on board a ship as a Cadet. This partial information provided for the purpose of providing contextual evidence for FRAM-DBN analysis. Specifically, the qualitative information is use to define the initial state of the function in a given time slice for DBN simulation. This simulation is designed with a high level of maneuvering ability such that the full potency of the participant to cope with the situation can be observed.

The event unfolds over approximately six minutes. In this scenario, the target ship is progressing from the northeast and moving towards the southwest. On the other hand, the participant's ship initially heads southwest, with the final destination also situated in the southwest. The challenge arises due to the target ship's higher speed compared to that of the participant. Therefore, the participant must navigate his ship adeptly to reach the destination safely while avoiding a collision with the faster-moving target ship. The details of the participant's decision-making process to address this situation are outlined in Table 2.

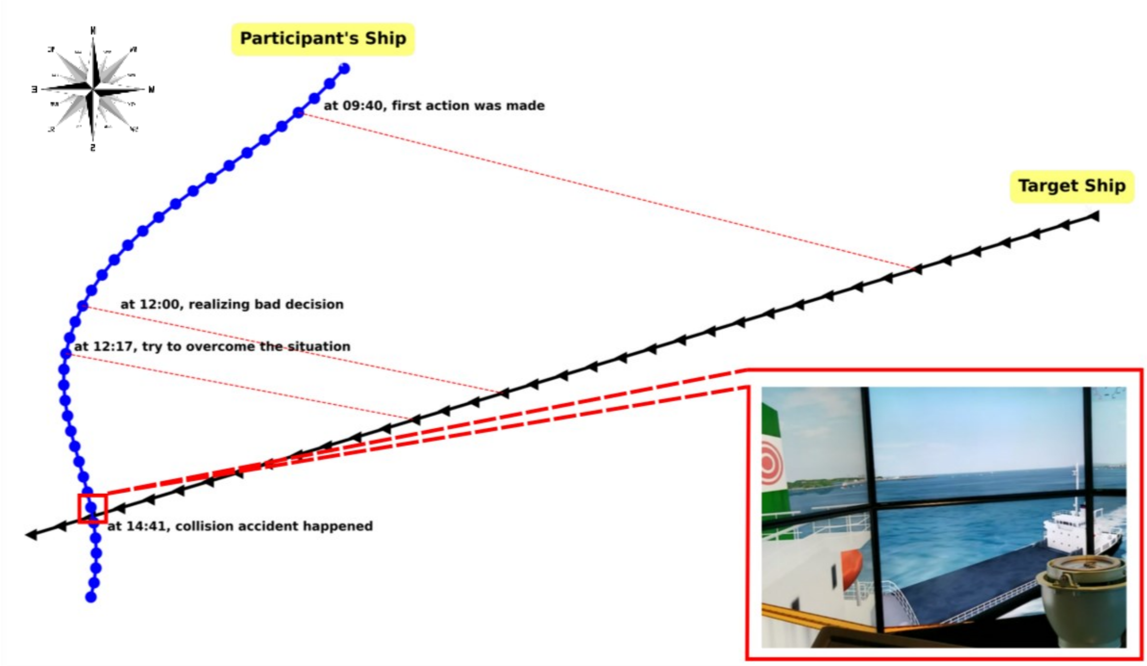


Figure 5.2. Ship trajectory of the simulation result (adapted from [94]).

Table 5.1. Time step and participant's explanation for each decision (adapted from [94]).

Step	Recorded time	Description
0	±09:00	Start to perform an action. Monitoring the target ship's situation and building a strategy to reach the destination.
1	±09:40	An initial decision has been made by ordering "Port 20." After seeing the radar and understanding the target situation, he made a sharp turn to the portside to avoid the target. The participant says, "I did not think much because the target ship was an overtaking ship and my ship was a maintenance ship. I admit that I have had a feeling of colliding at this moment."
2	±12:00	Continue to monitor the situation.
3	±12:17	Realize that the first decision was bad. He tried to overcome the situation by ordering "starboard 10" but did not work well. The participant says," At about 3:00, I was very embarrassed as the target ship approached. I could not think of anything at that moment. In fact, before making this decision, I should have asked the target about her intention."
4	±14:41	The collision accident happened

Five questions were asked of the participant for further understanding of his decision, including:

- When actually do you start to think to make this decision?
- What information do you need before making this decision?
- What makes you decide to take this action? Why did you do it at that time?
- What was your strategy to avoid this target ship at this moment? Do you have thought about that? Please explain.
- What factors do you consider the most to decide this action?

5.3 Result Analysis

5.3.1 Modified dynamic FRAM model and Analysis

Adhita et al. [61] have employed FRAM in the context of ship navigation to evaluate the resilience potency of the system. For simplification, the dynamic FRAM model for ship maneuvering during the simulation experiment has been introduced as shown in Figure 5.3. This model comprises five background functions, each representing a focal aspect for study, including <To monitor (by OOW)>, <To do direct lookout>, <To watch electronic devices>, <To decide action (make judgment)>, and <To control the rudder/engine>. The temporal changes in the function's dependency and function's updated role over time have also been presented in the model.

This simple FRAM model presented in Figure 5.3 illustrates the essential functional process of ship maneuvering activity observed during the simulation experiment. Key functions such as <To monitor (By OOW)>, <To do direct lookout>, and <To watch electronic devices> play crucial roles in the monitoring and learning processes. Initially, <To monitor (By OOW)> generates foundational information, including strategies and expectations regarding the current environmental situation. This information serves to activate the functions of <To do direct lookout> and <To watch electronic devices>. Once the information is collected, the system initiates the decision-making process to determine the appropriate response through <To decide action (make judgment)>. Subsequently, an anticipation strategy is formulated through the connection between <To decide action (make judgment)> and <To follow-up monitor (by OOW)>. This entire process of function activation is iteratively repeated over time until the target ship can be successfully avoided.

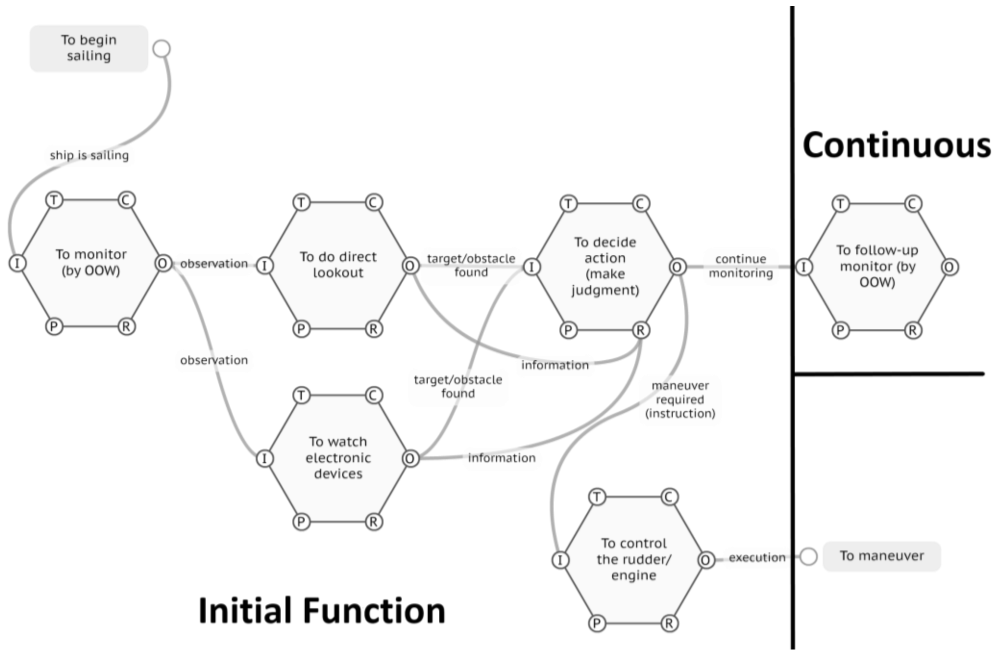


Figure 5.3. Simplified dynamic FRAM model for ship maneuvering in a simulation experiment (adapted from [94]).

This model highlights that the potential for functional resonance can be triggered in any connection between functions. Additionally, the continuous repetition of the function activation process can increase the emergence of irregular functional resonance. The more frequent the repetition, the higher the likelihood of irregular functional resonance emerging. The collision accident case, as explained in sub-subsection 5.2.3, serves as an example of how this resonance phenomenon influences function performance. An early indication of high variability performance from monitoring and lookout functions was detected around 09:40. This initiated the amplifying effect observed in the <To decide action (make a judgment)> function, leading to an undesired outcome—in this case, the order of "Port 20." The final adjustment was also executed "too late" in terms of timing, resulting in the inability to restore normal system functioning.

5.3.2 DBN for modeling dynamic performance in ship maneuvering

To perform DBN calculation, the FRAM model is first converted into a DBN model, as illustrated in Figure 5.4. The continuous expression is denoted by the edge with the number [1] on it. This edge signifies that the information in <To monitor (by OOW)> at t=1 is updated by itself at t=0 and <To decide action (make judgment)> at t=0. Then, the process is iteratively looped, mirroring the representation in the dynamic FRAM model. The specific time steps (t=0 to t=4) for iterating the calculation are determined based on the case study presented in sub-section 5.2.

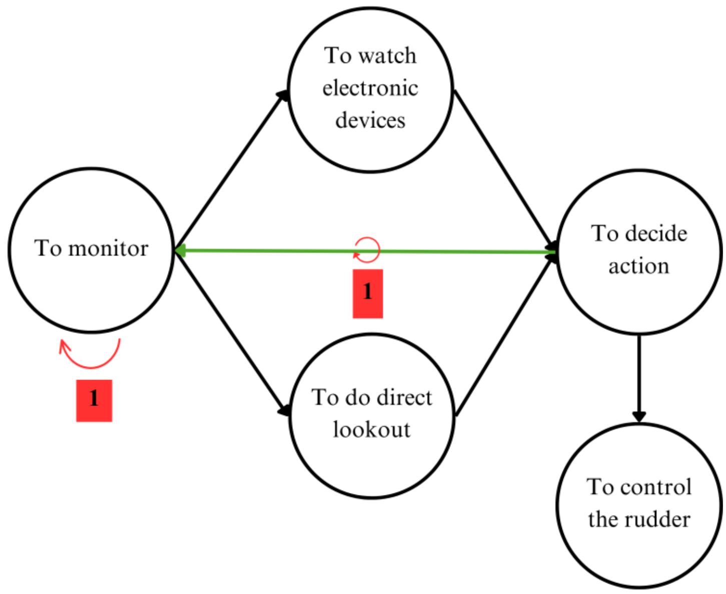


Figure 5.4. DBN model of Ship Manoeuvring Process (adapted from [94]).

Table 5.2. Example of discrete CPT for <To decide action> (adapted from [94]).

	To do direct lookout	Strategic			
	To watch electronic devices	Strategic	Tactical	Opportunistic	Scrambled
To decide action	Strategic	0.9558	0.45	0.0511	0.003
	Tactical	0.0442	0.545	0.6333	0.4226
	Opportunistic	0	0.005	0.3138	0.4854
	Scrambled	0	0	0.0018	0.089

The number of CPTs in the initial node set depends on the characteristics of the nodes and the number of edges pointing to each node. In total, 176 combinations of conditional probabilities for functions have been generated. As explained in subsection 5.2, these CPTs are determined by employing an adjusted description of control mode with common knowledge of ship navigation. For instance, <To do direct lookout> and <To watch electronic devices> are treated equally, signifying that these functions complement each other. In cases where one function performs in a "strategic" manner and the other in a "scrambled" manner, it influences the output of <To decide action (make judgment)> to be more likely "tactical" or "opportunistic," as presented in Table 5.2. This logical approach aligns with employing "if-then rules" in an intuitive manner.

The adjusted value of CPT is also considering the situation being assessed. It includes the familiarity with the situation in the simulation, the difficulty level of the encounter event given the participant's personal experience, etc. This considers important to produce reasonable results. The proposed DBN is intentionally exclusive for the case study.

Table 5.3. Example of discrete CPT for <To do direct lookout> (adapted from [94]).

	To monitor (by OOW)			
To do direct lookout	Strategic	Tactical	Opportunistic	Scrambled
Strategic	0.75	0.05	0	0
Tactical	0.25	0.8	0.1	0
Opportunistic	0	0.15	0.85	0.2
Scrambled	0	0	0.05	0.8

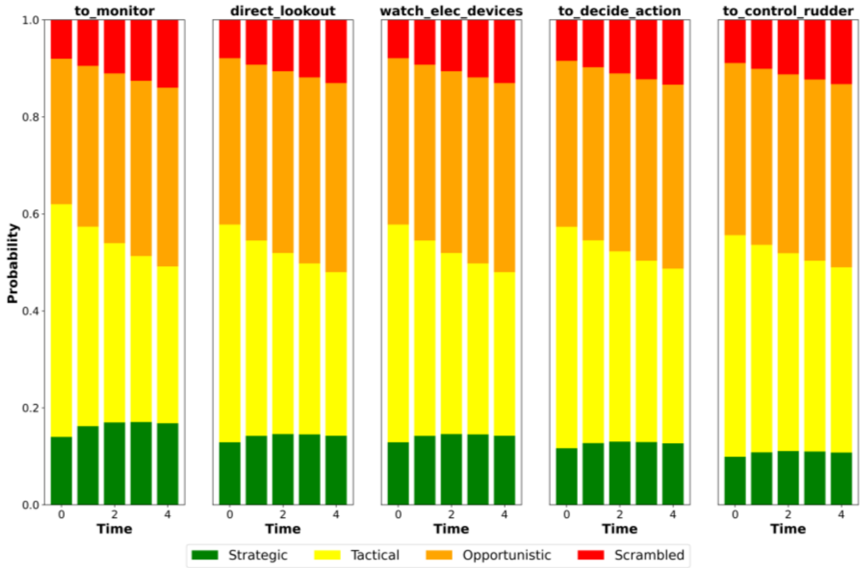


Figure 5.5. The evolution of expected normal performance of ship officer in each time step (adapted from [94]).

As a result, Figure 5.5 illustrates the expected normal performance of the officer in maneuvering the ship during the encounter event. The probability distribution indicates that the performance being strategic ranges from approximately 10% to 16%, tactical from around 32% to 48%, opportunistic from approximately 30% to 39%, and scrambled from about 8% to 13%. The fluctuations in each time slice represent the updated beliefs about performance due to the functions' dependencies, demonstrating a stable and reasonable evolution. This suggests that the provided CPTs and the proposed model for analysis have proven to be suitable for the intended purpose.

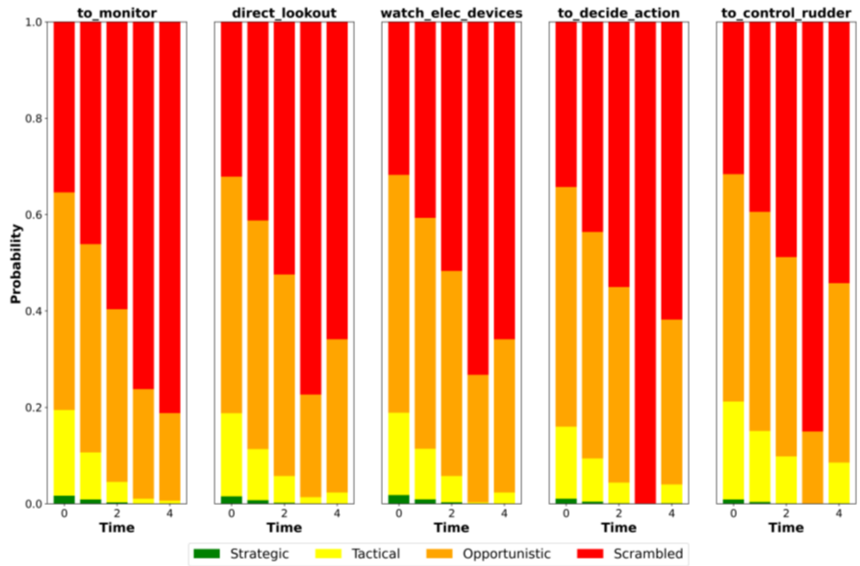
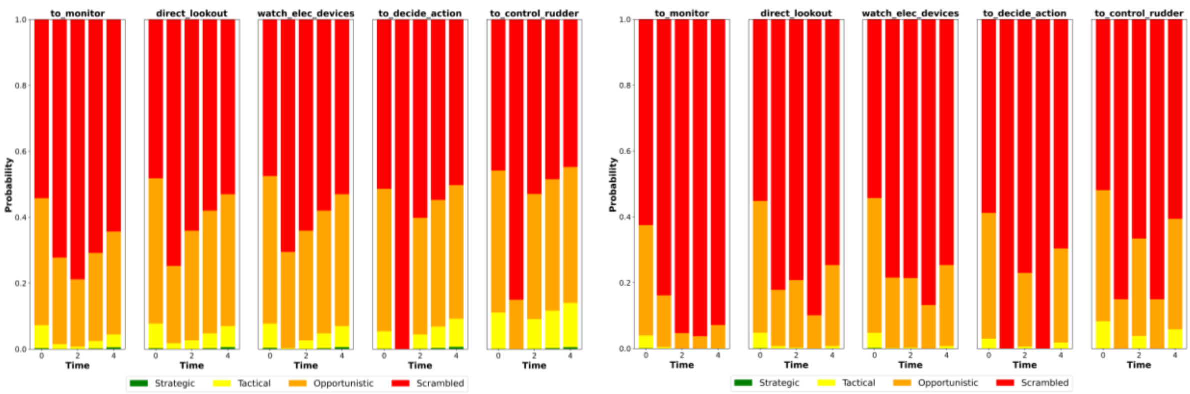


Figure 5.6. The evolution of performance in each function given the evidence of scrambled mode of <To decide action (make judgment)> at t=3 (adapted from [94]).

FRAM analysis has provided qualitative analysis for the case study. The fact that the emergence of a scrambled mode of <To decide action (make judgment)> at t=3 (±12:17) and speculation of the potency of functional resonance as well as the possibility of impact from the initial decision possesses important information for the DBN evaluation. Therefore, three assumptions are proposed to address the situation in a more explicit way.

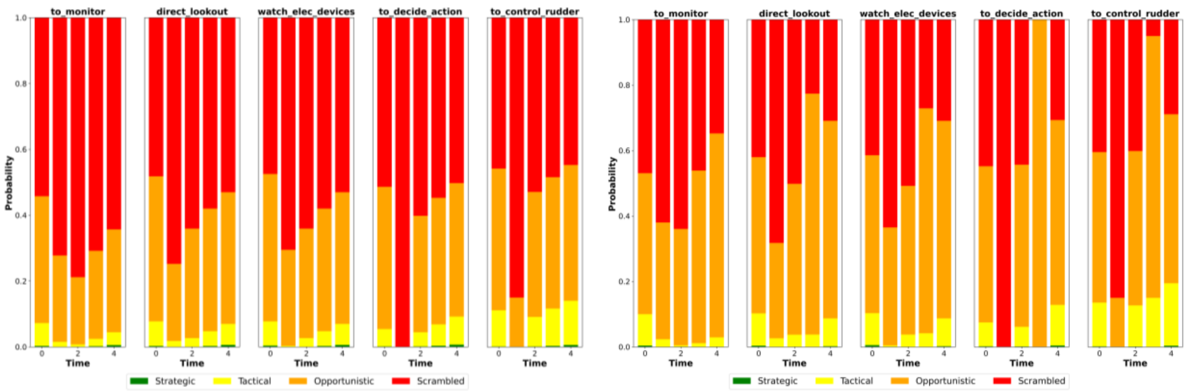
The first assumption: the fact that emergence of the scrambled mode in <To decide action (make judgment)> at t=3 (±12:17) is a significant factor. Figure 5.6 presents the potential situation leading up to t=3 and how the accident transpired at t=4. In this instance, the evidence for <To decide action (make judgment)> is set at 100% scrambled. It is evident that the probability of both scrambled and opportunistic modes before t=3 is increasing across all functions. Notably, <To monitor (by OOW)> indicates the most unfavorable situation among all functions. In addition, the probability of <To control rudder> being in a scrambled mode rises to more than 50%, underscoring the severity of the decision at t=3, ultimately resulting in the occurrence of the accident at t=4.

The second assumption: the first assumption shows that the drastic alterations in <To decide action (make judgment)> at t=4 strongly suggest substantial changes occurring in the preceding time step. This assumption is strengthened by the participant's acknowledgment that his initial action lacked careful consideration of the target situation. Consequently, Figure 5.7 illustrates the scenario where, at t=1, <To decide action (make judgment)> is in the scrambled mode, and the same mode reappears for the second time at t=3. This representation portrays a situation where all functions are thrust into an exceedingly unfavourable state.



(a) (b)

Figure 5.7. The evolution of performance in each function given the evidence of scrambled mode of <To decide action (make judgment)> at (a) t=1 and (b) t=3 (adapted from [94]).



(a) (b)

Figure 5.8. The evolution of performance in each function given the evidence of scrambled and opportunistic modes of <To decide action (make judgment)> at (a) t=1 and (b) t=3 (adapted from [94]).

The third assumption: the best scenario that was expected to occur. Given the second assumption, if the scrambled mode occurs at t=3, there is an anticipated 20% to 30% chance for the opportunistic mode to manifest in the subsequent sequence of function activation. If <To decide action (make judgment)> is set to be opportunistic at t=3, the outcome presented in Figure 5.8 illustrates a drastic shift in the system to the opportunistic mode, aligning with the expected scenario. This reflects how the situation might unfold if the participant attempts to communicate with the target ship, as mentioned. Moreover, it provides insight into potential adjustments if corrective action had been taken before 12:00 to address the adverse decision made at t=1.

5.4 Discussion

In this study, a case study involving a ship collision accident was selected to illustrate the degradation of system performance from a normal to a disrupted state. This choice of case study proved to be highly valuable, particularly in evaluating the dynamic changes in function performance over time. The proposed method not only enhances the comprehension of temporal dependencies among functions but also offers a nuanced analysis of their performance during the encounter event. The integration of FRAM analysis alongside DBN enriches the overall understanding of function performance. Furthermore, the proposed DBN has the potential to serve as a decision support tool for officers facing similar situations, providing valuable insights into expected performance and the potential consequences of various actions.

The analysis underscores the critical nature of performance adjustment in ensuring safety during ship maneuvering. The occurrence of the accident was attributed to the system's inability to generate an appropriate adjustment, evident in the impact of the target ship on the stern side of the participant's ship. This highlights that a marginally improved decision at t=3 to overcome the unwanted performance at t=1 could prevent the collision accident. Furthermore, the assumptions put forth in the DBN analysis served to illustrate the potential consequences of various decisions made by the officer, emphasizing the critical role of decision-making skills in ship navigation.

The Safety-II concept strongly advocates for an approach to safety that focuses on its presence in everyday operations. Despite the current study centering around an accident event, the intention is to offer a perspective on both normal and disrupted performance, explicitly presenting both situations. The significance of local adjustments in the ship maneuvering process has been emphasized. Across different instances in various time slices, the officer employs different strategies to adapt to the evolving dynamics of the operation. In this particular example, an undesired adjustment is highlighted, but an understanding of the expected course of action could also be provided. This underscores the need to enhance human performance flexibility for a higher level of ship resilience. Clearly, there exists a boundary for system flexibility in coping with a certain level of dynamic situations, and finding the right balance poses another challenge. Given the current trends in AI and autonomy, a higher level of ship resilience can potentially be achieved by integrating humans and technology through human-autonomous collaboration.

To enhance the depth of analysis in future studies, it is essential to explore modifications in the input data utilized for determining CPTs. Additionally, expanding the network could offer a further understanding of the specific factors influencing changes in performance over time. The flexibility and expandability inherent in the FRAM methodology, particularly with regard to its handling of "loose" couplings between functions, provide a promising avenue for further exploration. By considering these adjustments, future investigations can potentially solve more complex dynamics and contribute to a more comprehensive understanding of the complex interplay between a range of factors influencing system performance.

5.5 Chapter Conclusion

This study demonstrates the safety assessment in ship maneuvering events through a quantitative expression of performance variability using FRAM-DBN analysis. It has been observed that the utilization of FRAM-DBN analysis could be valuable for further development in analyzing the performance of ship officers during the maneuvering process. The continuous expression of changes in officer performance over time can be effectively demonstrated using the dynamic FRAM model and the discrete probability distribution of the function's performance mode in DBN. This detailed FRAM analysis reveals what is expected in the normal performance of ship navigation and how performance degradation occurred based on the case study being assessed. The application of this proposed method is currently limited to the case analyzed in this research. However, its potential for more complex implementations has been recognized.

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Chapter 6
Conclusion

The set of studies presented in this dissertation emphasizes the application of the resilience engineering perspective to enhance safety analysis in the maritime domain. The primary work involves analysing the resilience capacity of ship-officer performance during the navigation of a training ship in a coastal area. It holds a fundamental process to apply the resilience engineering point of view and express the actual work onboard in the form of the FRAM model. The study is expanded in a more contextual situation of ship navigation, that is a challenging ship-ship encounter situation. This aiming the applicability of FRAM analysis to provide an idea of how unique working adjustment produced by ship officer to maintain their system to functioning normally under unexpected situation.

Moreover, the elaborated version of FRAM has been introduced to strengthen the analysis through two distinct strategies. First, it involves combination of FRAM analysis with risk concept, utilizing risk as an objective reinforcement, which emphasizes the constructive collaboration of Safety-I and Safety-II for a more comprehensive safety assessment. The second approach extends FRAM with Dynamic Bayesian Network, aiming to highlight the explicit expression of function variability performance, thereby offering a more flexible analysis within the FRAM framework. It is also presenting a more flexible development for FRAM analysis through mathematical modelling.

In general, FRAM analysis showed the potential relation of the work on board at system's functional level. Specific characteristics of variability in timing, distance, and precision can distinctly classify the potential outcomes generated by the function. In addition, the extended version of FRAM proposed in this study has been found to significantly enrich and enhance the analysis results. Particularly, the contribution intended to be conveyed in this dissertation to the field of safety science in the maritime domain can be summarized as follows:

- *The FRAM analysis to elucidate the resilience potency in shipping operation.*

  This dissertation introduces the application of FRAM to analyse the resilience demonstrated in actual onboard ship operations. It highlights the significance of *Work-as-Done* wherein safety is embedded within the system through performance adjustments in a dynamic work environment. The ultimate proposal includes a functional model for the operation of a training ship. More specifically, it details the development of a dynamic FRAM model for ship manoeuvring during ship-ship encounters. This functional model illustrates the capabilities of human functions in dealing with sailing dynamics. The analysis, through the potential couplings, elucidates functional resonance, wherein the variability in performance may dampen or amplify, and endogenous and exogenous variability may also be involved. Moreover, this representation of potential functionality incorporates proactive countermeasures for navigating the constantly changing environment, e.g., ship traffic and dynamic weather, by leveraging the adaptive capacities of ship officers (humans). Thus, the detailed assessment within the proposed FRAM model has introduced an understanding of how today's shipping operations exhibit resilience potential in relation to ship safety, encompassing monitoring, response, learning, and anticipatory capabilities.

- *FRAM – Environmental Stress (ES) Model analysis for assessing proactive countermeasure perform by officer in challenging ship-ship encounter situation.*

In the simulation study, a practical understanding of officer's adaptability in challenging encounters was obtained based on the adjustments made. It provides a small example of learning from successful maneuvering against the inappropriate behavior of the target ship. More importantly, the integration of Safety-II and ES models (risk perspective) further elaborates on the analysis, providing more context and value to the decision-making of participants.

The analysis of the FRAM with the ES model integration marks the initial effort to incorporate risk and resilience perspectives for safety assessment in the maritime domain. This study primarily emphasizes the elaboration of FRAM within a particular context. However, its wider application has also been recognized. The combination utilizes quantifiable data in the ES model to objectively support FRAM's explanation of the officer decision process. This constructive collaboration effectively utilizes the shared characteristics between variability assessment in FRAM and the quantification of parameters within the ES score. The results suggest that a decrement in the ES score expresses a potential dampening of performance variability. Moreover, this finding aligns with the framework proposed by Logan et al. [44], which defines a resilient system as one where the risk of producing the undesired functionality is sufficiently low.

The data analysis indicates the potential to enhance system adaptability and flexibility, especially related to communication function and early response. A successful ship navigation perspective provides a unique reflection of real-world performance (WAD) in handling day-to-day operational dynamics. Additionally, recognizing the significance of continuous local adjustments as a fundamental safety factor highlights the variability in maneuvering decisions. While these decisions are frequently successful in achieving desired objectives, they might occasionally fail, but at an exceptionally low frequency.

- *The extended version of FRAM analysis with Dynamic Bayesian Network (DBN) offers a flexible assessment method for evaluating the potential variability in function performance.*

  The aim of this elaborated version of FRAM was to provide a direct representation of function performance variability. By incorporating Dynamic Bayesian Network (DBN), a temporal mathematical model, we sought to illustrate changes in officer performance over time. This combination tried to develop a flexible FRAM assessment for analyzing the performance of ship officers during the maneuvering process. The analysis suggests that the dynamic FRAM model, combined with the discrete probability distribution of the function's performance mode in DBN, allows for a comprehensive and continuous representation of changes in officer performance over time.

  The method's application is exemplified by the analysis of collision scenarios captured in ship handling simulations. This example illustrates the shift from normal to disrupted system performance and highlights the expected proactive countermeasures to maintain normal functionality. The collaboration between FRAM and DBN has been instrumental, particularly in assessing the dynamic changes in function performance over time. The DBN analysis complements the FRAM assessment, offering a deeper understanding of function performance during encounter events. In addition, this proposed DBN method can serve as a decision support tool for officers in similar situations, providing insights into adaptable performance and potential consequences of different actions.

This current resilience perspective adoption for analyzing Officer performance shows a potential application in a more complex merchant ship operation. However, the model of the whole process of ship operation requires further study to be implemented generally. In the broader context of shipping operations, a ship relies on various systems, such as vessel traffic service, pilotage, and shore representatives. The proposed FRAM model could be expanded to encompass a more complex shipping operation. A deeper understanding of function variability performance could offer more effective proactive measures to enhance ship resilience. This insight is also found invaluable for further exploration of safe ship navigation from a resilience engineering perspective. For instance, it could aid in developing simulation training that accelerates the navigation skills of younger generations based on the successful maneuvering experiences of professional seafarers. Human adaptability in today's complex sociotechnical system remains the key to dealing with complexities in systems.

Furthermore, the extended version of FRAM analysis presented in this dissertation contributes to the field of resilience engineering, particularly in the maritime domain. While the FRAM-ES and FRAM-DBN are presented separately, their integration highlights the potential for a comprehensive safety analysis by integrating traditional safety approaches with resilience engineering. Future work may explore synthesizing these efforts into a unified framework capable of not only reactive and proactive measures but also harnessing positive surprises for system performance enhancement. Such a unified solution can draw insights from both successful and failed events to understand system complexity.

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List of Publication

Journal Papers

- Adhita, I. G. M. S., Fuchi, M., Konishi, T., Fujimoto, S. (2023). Ship navigation from a Safety-II perspective: A case study of training-ship operation in coastal area. Reliability Engineering and System Safety. https://doi.org/10.1016/j.ress.2023.109140
- Adhita, I. G. M. S., Fuchi, M., Konishi, T., Fujimoto, S. (2023). Modelling Ship Officer Performance Variability Using Functional Resonance Analysis Method and Dynamic Bayesian Network. TransNav Journal. http://dx.doi.org/10.12716/1001.17.04.13

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