Author: Alexandros K. Rammos

APPLICATION OF THE FUNCTIONAL RESONANSE ANALYSIS METHOD (FRAM) ON FIRES ONBOARD SHIP

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LABORATORY FOR MARITIME TRANSPORT

0. Prologue

This paper is inspired by several months of research in safety management and incident investigation. The author's involvement in training courses on emergency response and damage control onboard ships and the related scientific research on these topics settled the foundation of knowledge for this study.

Ignorance of remote causes, disposeth men to

attribute all events, to the causes immediate,

and Instrumental: For these are all the

causes they perceive.

Thomas Hobbes. Leviathan, Chapter XI (15881679)

I would like to thank all the experts that provided the help I needed, anytime I did, as well as all the people that inspired me to focus on the subject of safety. I also want to thank all those who supported me during this time.

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1. Introduction

Incidents challenge the current strategies incorporated in safety management in a way that they provide positive feedback for further improvement. It is a fact that safety –in the sense of lack of incidents, which is a topic that will be discussed further in this study - has improved in recent years. Newer legislation, technology and rules have significantly contributed to the reduced number of incidents. Yet, incidents still happen, and the investigations usually focus on design failures, faulty installations, poor maintenance, human negligence and wrong procedures. This suggests that the aforementioned factors are not always adequate for a complete model of safety.

Through the first ages of safety, where technologic failures were the commonly thought reason for incidents, to the ages of blaming human factors or -later- organizational errors, and through models that either improve specific responses or strengthen the barriers, the question remains unanswered. The work-as-imagined and work-as-done gap and the variability in several needed actions turn the focus on system component interactions to create a more resilient system, designed to anticipate external hazards.

This paper is motivated by the increasing number of practitioners and scholars with an interest in modeled resilience approaches to incident investigation and the presumed upon lessons-learned that come by those incidents.

The potential of the Functional Resonance Assessment Method (also referred to as: the FRAM) to provide a deep investigation in the dynamics of an incident, to redeem lessons-learned in a more efficient and out-of-the-box path and to evaluate both the obtained lessons and the tool's ability to evaluate resilience characteristics is explored. In brief, this method is selected because it dares to accept that the design process requires certain ignorance regarding the external hazards the system may be subject to, a pool of hazards that the designer cannot be expected to foresee. That is also true for other factors as well, as the human element and even the behavior of technical equipment vary through time, age, load etc.

This thesis studies a relatively new method to investigate incidents and create a Functional Resonance Analysis Method model of the system that failed. This model may highlight nodes that were subject to failure and that would otherwise be neglected, resulting in the reoccurrence of an incident. With the combined help from damage control experts' suggestions are made for the improvement of the system. For the process of identifying the needed functions, a common framework is needed as a part of future research. This research required a thorough review in current literature and various data from incident investigations where the support by fire training experts that were consulted was crucial.

This thesis researches the potential of the Functional Resonance Analysis Method to provide deeper understanding on fire incidents onboard ships as well as proactive and reactive control for such occurrences, with a focus on emergency response. At first, the effective use of the Functional Resonance Analysis Method for fire incident investigation from a systemic perspective is explored. Later, the feasibility of incorporating the Functional Resonance Analysis Method to provide suggestions for improvement is attempted and evaluated. Through the research, the method's ability to obtain lessons via investigating is dominant.

While the common practice instructs the elimination of the hazards that caused any given incidents, the analysis from a systemic perspective supports the resilient operation of the system. In addition to attempting to reduce the number of occurrences, the system should become more responsive to those inevitable disturbances.

The focus of the research is to utilize the Functional Resonance Analysis Method to be applied in emergency response on fire incident on board ship. The procedure in such events is not as deterministic as other routine operations and hence, the analyses of the functions derive from the official investigation report, as this real-life scenario is the most realistic system response available.

To achieve this, an instantiation for each of two selected incidents (the incident in Commodore Clipper, chapter 5.1 of this study and the incident of Edinburgh Castle, chapter 5.2 of this study) was analyzed. This required extensive review of the available data of the event and each one is narrated with emphasis given on the ones that will be further analyzed.

Due to the fact that the tool currently lacks quantitative calculations, the suggestions are provided solely by studying the interactions between functions, where FRAM excels. Additional suggestions for further research in combinations with the innovative fields of Machine Learning and Big Data analysis are given in the last chapter.

2. Theoretical Background

2.1. Safety

2.1.1. Safety-I and Safety-II

The traditional view of safety requires an incident to happen in order to analyze and collect feedback for future occurrences of a similar event. The feedback is the focus of the safety research to make suggestions for a more efficient system. This view is called safety I since the addition of more modern schools of thought in safety research. The alternative view, called safety II accepts that ‘things go wrong’ for the same foundational reasons they “go right”. With respect to resilience engineering (discussed in more detail later in this chapter) this safety model analyses how the positive outcomes from everyday work are successful through varying external and internal factors. (Hollnagel, 2004)

In general, technological systems are reliable (Hollnagel, 2004). Thus, safety investigates the root causes in unreliable factors of the system, i.e. humans and their performance. This approach’s focus on cause-effect relationships restricts the available data pool since incidents and near-misses occur far less than the everyday tasks that are successful. Thus, does not take into account the inevitable variations that are needed in real life operations.

When a system is designed, each component is expected to work as designed and as instructed by external factors as authorities and regulations. However, in real life conditions the designed procedures frequently have high variations from the expected outcome. This work-as-imagined and work-as-done gap, with the latter meaning what actually happens, is responsible for faulty predictions on real life situations. Safety-I suggests that failure is rooted in malfunctioning of a system component while Safety II attempts to adapt to those inevitable variations and adjust according to the current conditions in any procedure. These everyday variations are the causes of both the positive and negative outcomes.

A large number of incidents are preventable with relative ease in hindsight, but the solutions are usually highly customized on very similar future occurrences. This poses a limitation to their change inspiring potential, as simple fixes or rushed decisions may not always apply on any system.

2.1.2. From Safety to Resilience

Human error is widely considered to be the cause of different malfunctions, namely in organizational context. That means that the behavior of an operator is not solely based on his individual decisions, but also in other factors. The safety assessment methods need to study the effects of the functional couplings that are created between the organizations and the personnel operating the system. This incorporation of the relations between the different components of a system can significantly attribute to the exploration of the underlying causes.

The analysis of the Roll on/Roll off Herald of Free Enterprise incident became a pioneering-work enhancing the responsibilities of the shipping companies (IMO, 2010). This was the incident that made the need of more holistic assessment methods, able to identify the causes and prevent future incidents in a way that methods to that day were not as efficient.

Through the ages of safety, the focus tends from negative to all the outcomes. Safety research used to rely on reducing the number of adverse effects by eliminating all malfunctions and even all failures as far as possible. As our experience in safety management increases, the system and procedure design increases in ability to respond when something happens and be able to succeed under varying conditions. Thus, the goal is shifting to increased resilience, with a system able to respond to uncertain adverse effects.

The idea that safety is emerging from the varying interactions between the system components is expressed by Robertson et al. (2015), Vinerbi et al.(2010) and Mitropoulos and Cupido (2009) and others.

Hollnagel et al. (2007), Carayon et al. (2015) study safety through the interactions across components, as an emergent property of sociotechnical systems. The components may be organizations, human behavior software and any other system interacting. The use of the term emergence was by Lewes 1874, describing how to express a system as a resultant of the components' outcomes, where those outcomes are of different nature from each other.

2.1.3. Resilience

Resilience is the ability to recover and adjust easily to change. It is, by other words, the ability to absorb a disturbance and then return to the original condition unchanged. The term also refers to the ability to learn from these occurrences and be better prepared in future disturbances.

The principle is not to avoid disturbances but to be able to absorb them and obtain lessons. A more resilient system is capable of absorbing greater disturbances and then return to usual condition and function as effectively.

Other definitions of resilience describe it as the ability to address and properly respond to regular as well as irregular disturbances, to know what to look for and be able to monitor anything that may become a threat in the near future. Being able to anticipate the potential hazards creates a proactively safe work environment.

This approach offers room for further improvement in terms of safety and efficiency, combining human benefits with commercial benefits, by overcoming the existing limitations. Such benefits may further increase the interest in resilience.

Safety in recent years is increasingly becoming a matter of managing performance. The variations in performance are necessary for proper functioning and inevitable. Thus, it must take into account the changes a system component's performance may be subject to. The aim is to create a system that is able to adjust primary functions in case of a disturbance and then be able to work as before. As a property, a system's resilience is difficult to be measured accurately.

Five Key resilience Characteristics are described in the table below (Table 1) (Woods 2006).

Buffering capacity	The quality and magnitude of disruptions the system can adapt without a critical breakdown in performance.
Flexibility versus stiffness	The ability to restructure in response to disturbances and changes
Margin	How closely the system is operating relative to some kind of performance boundary
Tolerance	How a system behaves near a boundary, the severity of the collapse or the dampening effect

Table 1 Key resilience Characteristics

Cross-scale interactions are critical as the resilience of a system defined at one scale depends on influences from scales above and bellow

2.2. Incidents Onboard Ship

It is my sincere wish — and hope — that the day will come in the not far distant future — when the protecting arms of Universal Safety will spread out over all industry and reach directly the millions of workers who make industry possible.

Charles M. Schwab, "New Values in Industry," 1929

Our investigation focuses on fire incidents onboard ships, as one of the most dangerous emergencies onboard. The same principles may be applicable to different kinds of incidents but those are out of the reach of this thesis.

2.2.1. Incidents in the Maritime Environment

Ship operation and maintenance create a hazardous environment for crew members making it difficult to deal with the multitude of incidents that can occur by both the everyday routine operations of the crew and the machinery as well as the external random events such as extreme weather conditions. One of the greatest dangers for the ship is the fire outbreak, since even the smallest occurrence can lead to catastrophic results, with the crew unable to control the fire in open seas. There are many protocols established to tackle this issue and make fire detection and extinguish a viable goal, however, most of the measures aim to mitigate the damage until external help arrives. Hence, the most effective way to deal with fires on board ships is to prevent them in the first place, instead of trying to fight them, when it is possible **(**15 May 2015, www.sipownersclub.com, Fire prevention on board ships***)*****.** That being said, ignition (fire break out where no fire exists) and flash (fire eruption in new place because of pre-existing fire in a near compartment) are the events that must be proactively managed by the crew.

2.2.2. Incident Investigation

Incident investigations combine elements of different fields of science as well as what we might characterize detective work. Analyzing samples, testing materials in the laboratory, failure modes, all are scientific processes that provide the necessary data for the investigation. The reason of the failure is chosen by the investigator among different reasons such as fatigue failure or improper maintenance and neglect. This valuable process:

- Discovers the hazards that led to the incident to prevent their recurrence.
- Discovers additional hazards in the course of the investigation

This process requires complex analysis since no incident is caused by a single hazard or factor but by the combination of multiple failures and their interaction in the given moment.

Incident investigations are conducted for both legal (claims, insurance, compensation, lawsuits) and safety (prevention of future incidents and their associated physical, emotional and material costs) reasons. However, even for different purposes, for both reasons the primary outcome is the prevention –or even reduction- of future incidents. It is important to note that the outcome is more reliable in safety investigations when the blaming is out of perception.

The process of incident investigations is the same for both major incidents and lesser ones. Even though more focus is given on major incidents the lessons-learned obtained by the investigation may be of equal value. *Even near-misses, unplanned events that did not cause but had the potential to cause an incident, are of intrinsic value as a glimpse over the edge of the system's capabilities.*

The common issue with incident investigation is the "you find what you look for" principle, meaning that the assumptions first made about the causes of the incident usually guide the analysis and often neglecting major weaknesses that remain hidden.

2.2.3. Fire Onboard

Fire onboard is one of the most serious risks for both the crew and the property. On board ship there are tons of stores of flammable material, liquid fuel, air-conditioning plants, engines, electrical equipment, boilers, and accommodation (kitchens, mess rooms, lounges, cabins, WCs). Then we must add the cargo which usually consists of at least partly flammable material or even dangerous chemicals. In the case of passenger ships, the same holds true for cars and increased accommodation as well as passengers unfamiliar with the hazards. Since the ship is, by its nature, all of its life cycle on sea, the effects of fire onboard can be devastating when combined with external hazards such as extreme weather conditions or simply the inability to get additional help from ashore. Thus, fire onboard frequently results in loss of life, precious cargo or environmental damage-since the vessel may be inoperable. When the wrong rescue methods are employed, for example the indiscriminate use of large quantities of water, the ship may be lost as a result of instability, and not because of the fire. Garri G. (1992)

2.2.4. Safety Guidelines

Regulation 2 of chapter II-2 of SOLAS sets up fire safety objectives to prioritize and emphasize the key points of interest in regards to fire safety.

1. Prevent the occurrence of fire and explosion
2. Reduce the risk to life caused by fire
3. Reduce the risk of damage cause by fire to the ship, its cargo and the environment
4. Contain, control, and suppress fire and explosion in the compartment of origin
5. Provide adequate and readily accessible means of escape for passengers and crew.

2.2.5. Functional Requirements

Proactive safety guidelines (SOLAS, regulation 2 of chapter II-2, for this matter) regulate a number of requirements in ship construction and operation to prevent and reduce risk of life and material damage.

1. Division of the ship into main vertical and horizontal zones by thermal and structural boundaries
2. Separation of accommodation spaces from the remainder of the ship by thermal and structural boundaries
3. Restricted use of combustible materials
4. Detection of any fire in the zone of origin
5. Containment and extinction of any fire in the space of origin
6. Protection of means of escape and access for fire fighting
7. Ready availability of fire-extinguishing appliances
8. Minimization of possibility of ignition of flammable cargo vapor.

2.3. Emergency Response

In the maritime industry, the emergency response refers to the system’s response to situations that may cause serious damage or sinking of the vessel. Such hazards are for example fire onboard and flooding (either due to rupture, hatches left open, excess firefighting use of water etc.). The term “Emergency Response” is found on warships as “Damage Control” and in this thesis; the two terms are used interchangeably.

Each of these damage control scenarios require a unique damage control method utilizing all the vessel’s defenses, be it active equipment or crew and squads. The crew must be properly trained since usually, immediate rescue from ashore is not an option. The purpose is to maintain the seakeeping until external help arrives or the vessel is safe at dock. The procedures followed during damage control are detailed to ensure effectiveness in order. However, it is important to note that order, is particularly hard to keep during these emergency situations when the whole system is under extreme load.

2.3.1. Evacuation

In response to fire or flooding, evacuation procedures have two main phases: 1) mustering and 2) abandonment. Mustering refers to the relocation of the crowd in a safer position on board the ship and the procedure is initiated by a unique alarm, calling the passengers to summon in a muster station. Abandonment refers to the embarkation and launching of the lifeboats. Nevertheless, search and rescue should be considered too.

The most safety-critical asset during this procedure is time. Evacuating a large passenger-ship involves moving thousands of people safely between different parts of the vessel. Such a process is highly demanding on the vessel’s resources, as crew-personnel and decision-making. The latter becomes increasingly complex when the evolving and dynamic nature of the crisis is considered. Given the limitations of human functions, assuming that the passengers will behave as expected and follow instructions is not advised.

IMO SOLAS Chapter II-2, Part D, Regulation 13 – ‘Means of Escape’, as it was amended under Resolution MSC.404(96) makes evacuation analysis a mandatory requirement for new passenger ships constructed (keel lay date) on or after 1st January 2020, when carrying more than 36 passengers. It recommends the use of MSC1/Circ. 1533 [2], which provides the Revised Guidelines on evacuation analyses for new and existing passenger ships. These guidelines offer a simplified and an advanced method for conducting the evacuation analysis. The input for the simplified method was based on measurements of people movement in land buildings which share physical similarities (dimensions, reproducible light conditions) with ship evacuation.

Unfortunately, the operational requirements of passenger ship evacuation are not equivalent to those of buildings on land – e.g. the behavior of the people involved - which has led to many experts criticizing the current guidelines. In addition, extreme conditions, fire and flooding hazards render the current regulatory instruments insufficient.

The required evacuation procedures on-board ships are far more complex to a building where the only requirement is to find and navigate to the nearest exit points. Passengers are instructed to return to their cabins to collect lifejackets before heading for a pre-defined assembly (or muster) station. They must then exit the ship by getting to lifeboats, life raft and possibly evacuation slides, for which they have no training and in some cases are very reluctant due to arrangement of equipment (e.g. use of chute), physical limitations or even personal ones (e.g. elderly or claustrophobic people). The ship is floating on waves and this may result in significant motions and accelerations. Furthermore, in case of flooding, it may list or even capsize rapidly.

2.4. The Human Element

Human performance, either for individuals or for small groups of people, is considered to be highly variable. There are many factors that can hinder human performance but more importantly the same factors result in unexpected variations in everyday work. The role of the human element on fire incidents onboard ships is described in the following paragraphs.

2.4.1. Human Factors Triggering Human Error

Human factors affecting safety can be divided into organizational, group and individual factors. Some examples of organizational factors are management commitment to safety, safety training, open communication, environmental control and management, stable workforce, and positive safety promotion policy. Examples of group factors are line-management style, good supervision and clear understanding of own and other team members' roles and responsibilities. Individual factors are related to factors which affect a person's performance such as human-machine interface and competence, stress, motivation and workload of an individual. (Gorgon, R. P. E, 1998)

2.4.2. Crew Performance Variability in Fire Incidents

Fire is the most common and dangerous emergency on board ship and have already caused disastrous results in regard to life loss. Fire Safety systems fail unexpectedly. Engineering make steps and even leaps in the safety zone but still, fire incidents remain quite common.

Thus, the most important aspect of fire prevention is the crew itself.

And crew performance is the most difficult to predict aspect of our investigation. In brief:

- The crew must be trained thoroughly and regularly (as recently regulated by IMO with the mandatory update of the STCW training every five years (International Shipping Federation (2011))
- The training should include use of simulators to replicate the conditions of an actual emergency since it is common knowledge that humans behave differently in cases of life-threatening events
- Even after successful training, crew members have to deal with a number of factors that affect human behavior and performance such as sleep deprivation and irregular sleep patterns, motion sickness and even boredom on board.
- Other human factors like fatigue and stress on top of other duties onboard (since there are no dedicated firefighters onboard)

All these factors should be considered as well since a large number of incidents are at least partly due to these human limitations.

2.4.3. Human Element Performance with regards to incident stage

Data from incident investigations result in three major phases that human interference can affect the voyage. Hence, there are three general categories that the human factor can negatively affect the safety of the vessel. These are the result of the safety protocols not properly followed, for whatever reason.

Fire initiation

As seen in the collective data, crew members (and also passengers) constitute a serious fire hazard onboard ship. From cigarette flames to inattention in the kitchen, human negligence to rules and regulations designed to prevent such events can initiate a small but potentially catastrophic fire.

Late detection

Perhaps the most common negative effects the human factor can have on board is caused by negligence, either willingly or unintentionally. Conditions on board, continuous false positive alarms, stress and fatigue make everyday tasks greatly harder and often distract crew members. Thus, events like alarm bypasses become common as do rushed checking and not paying attention during scheduled and unscheduled patrols.

As noted before, the crews' and the vessel's best chance of survival is fire prevention and early detection to take action. If the fire spreads, the chances of survival drop significantly.

Failure to mitigate damage

A common fire cause is the ignition of pressured sprayed oil in hot surfaces of the engine room. This is a risk that cannot be mitigated by human factor optimization. However, even in an event of an already developed fire, the firefighting code provides with methods to mitigate the damage through standardized procedures and protocols. As noted in the aforementioned investigations, a fatigued crew that may have not had the proper training in realistic environment and in realistic conditions may find the event extremely stressful, significantly interfering with the performance with potentially catastrophic results. (Ventikos N., Lykos G., Rammos A., Petropoulos V., 2018)

2.5. What Skills can be observed

2.5.1. Human limitation- Stress and Fatigue

Stress has been identified as a contributory factor to the productivity and health costs of an organization as well as to personnel's health and welfare (Matsidi Vasiliki, Papaleonida Paraskevi, 2014). Stress arises in highly demanding tasks as a bodily response to the fight-or-flight dilemma. It is important to note that high stress levels impair human performance making individuals more susceptible to errors. If those effects are chronic then the implications on the individual's health are heavily taxing and this fact should not be ignored. When the human limitations are exceeded the stress response is high and if not properly managed it can significantly affect one's performance and behavior. The acute effects of a high stress response range from impaired decision making and faulty situational awareness to reduced physical capabilities and decreased performance. High baseline stress levels also induce absent-mindness, increasing the chances of errors in everyday routine tasks. The mitigating methods include proper and realistic training that change the perspective of the individual, making the task seem closer to his capabilities than if were untrained.

The demanding conditions of work in the maritime industry, resulting from e.g. more hours on duty and short passages, create an exhaustive environment leading to decreased crew's performance. This can increase the number of errors occurred by human mistake (Matsidi Vasiliki, Papaleonida Paraskevi, 2014). Studies that focus on questionnaire analysis have found that 17% of watch officers have fallen asleep and 40% have been near nodding off on watch (Matsidi Vasiliki, Papaleonida Paraskevi, 2014). The causal factors of fatigue that lead to decreased performance are summarized in the table below:

Table 2 Factors that lead to decreased performance

Workload	Harder work in larger volume requires additional time for recovery
Sleep dept.	The absence of sleep makes the crew more fatigued and decreases their attention
Perceived risk or interest	A demanding task may keep the crew alert, but the accumulative fatigue increases the need for recovery. Boring tasks may increase fatigue too.
Time of the day	While the vessel needs the same constant level of attention, human performance varies during daytime and nighttime.
Environment	The ship's environment is demanding and tiring and the decreased quality of rest increases fatigue accumulation.[6 human error].

Communication difficulties decreased attention and vigilance, mood changes, omissions and carelessness, inability to concentrate and faulty memory are common signs of accumulated fatigue. (Matsidi Vasiliki, Papaleonida Paraskevi, 2014)

2.4.2. Non-Technical Skills

Situational Awareness refers to the perception of the events and the elements in the surrounding environment and one's ability to understand their meaning even after a variable changes. In other words, it is to be aware of the impact one's actions make in any given situation.

It is a very important aspect in emergency responses since the hazardous environment of these situations change the surrounding environment rapidly, making it difficult for non-stressed decision making.

Communication and Teamwork are another important non-technical skill. Unlike technological systems where the communication is via predesigned pathways, humans often find it difficult to communicate with each other, especially under a stressful situation, as is an emergency response. Even if certified and agreed in the use of a common language, emergency responses lead to the use of the native language. This is often the case during life-threatening situations. Reduced communication results in decreased efficiency as a team since teamwork is impaired.

2.4.3. Organization Failure

There are three main causes for organizational failure:

Insufficient Training and Inadequate Manning: Any organization is responsible for the training of their crew members. Through this repeated training the crew gains valuable technical and non-technical skills, useful in any situation. Crew members are responsible for a number of tasks on board and that includes damage control. Hence, they are trained in simulated environments such as Fire simulators that create a realistic environment for them to train and test their abilities and skills. If this important part is ignored, procedures are not followed correctly and that has many implications on other aspects of the system, as this study tries to expose. Inadequate manning also poses a safety risk since the quantity of tasks may rapidly increase in an emergency scenario.

Safety Culture: A philosophy promoting safety as the ultimate consideration for all company personnel and applied to all activities undertaken both ashore and at sea

Working Environment: Environment can affect crew performance both directly and indirectly. The marine environment has crew members face currents, winds, fog and extreme weather conditions to name a few. Proper work schedules and design feature can help improve the working environment.

3. Methodology

There are numerous analysis methods for complex systems available that also provide visual presentation and analysis techniques. Among these methods are Cognitive Work Analysis (Vicente, 1999), AcciMap (Svedung & Rasmussen, 2002), system dynamics (e.g. Senge, 1990), and various enterprise architecture frameworks (e.g. Johnson & Ekstedt, 2007). Application of the Functional Resonance Analysis Method (FRAM; Hollnagel, 2012) is done textually but invites for the visualization of analysis results in a loosely-defined manner, e.g. through illustrating instantiations.

This chapter describes the approach of this thesis. Beginning with a review in existing literature where the Functional Resonance Analysis Method is used in different ways and different industries, the theoretical background needed for the use of FRAM in this study was collected and reviewed. The purpose of this study, after evaluating the use on fire incidents onboard, is to create a common framework on FRAM functions involved in fire emergency responses through different types of vessels. This framework is more complete case by case making the use of the FRAM practical to be incorporated for future investigations, since the naming and couplings will be preexisting. Additionally, new scenarios could be tested and assessed. Fire incidents where chosen as the target for the investigation and the reports were collected by investigating agencies.

3.1. Application of FRAM

FRAM is a relatively new method that is capable to analyze the interactions within simpler and more complex social-technical systems. This method is chosen over traditional fault-finding methods where systems are assumed to work as intended and as designed unless there is a fault or malfunction in the component itself. While this assumption may be true for most technical systems it fails to include the many cases where human performance is highly variable and unstable, depending on external and internal factors on the system. FRAM relies on proper understanding of what should go right, either for future or past investigations. Examples of future investigations are assessment scenarios and examples of past investigations are incident investigations where the researcher has knowledge of the outcome in hindsight. This assist the indulging on work-as-done and work-as-imagined gap, highlighting the ways variability played or may play an important role in system performance and, hence, the outcome.

It is important to note that each incident requires a dedicated instantiation of the FRAM model that describes the event as it happened.

Incident investigation from a FRAM perspective does not look for a cause to be initiated but tries to understand what should have gone right. Then, the investigator analyzes the variability of each function and suggests the causes based on this analysis. It is possible to make suggestions on this analysis alone or even suggest additions to the system that may reduce future incidents.

Pro rata, the use of FRAM for risk assessment first describes the system with every function as should perform and then suggests how variability on any function may hinder the performance of the system as a whole. This reduces the need for complex scenarios that may fail to include a number of existing variability factors.

Thus, a proper understanding of the procedure being analyzed is required. As seen in the literature review, the proper understanding of the different functions often limits the research or adds complexity for the researcher, making the use of the method harder. This thesis suggests the creation of a common framework as code of reference for future investigators, offering the ability to add any new given function that may be encountered for the framework to be completed. This may have practical application in large scale investigations as in fleet managing. Suggestions are also made based on this framework.

FRAM is based on four principles (Herrera & Woltjer, 2010; Hollnagel, 2004):

Table 3 The Four principles of FRAM

• Fails and successes derive from the same reasons. The factors for a successful operation are the system's capability to anticipate risks, be able to recognize and monitor the risks and ultimately, risk management. (Herrera & Woltjer, 2010)
• When the variability of several functions resonates, this variability might exceed the normal limits and result in an incident (Hollnagel, 2004).
• When variability of different and multiple functions resonate, the outcome of later functions varies in an unexpected way. (Hollnagel, 2004).
• Socio-technical systems are highly adaptable and adjust to the threat or workload posed each time. This variability is necessary to control the function. The variability of one function is usually inadequate alone to cause an incident (Hollnagel, 2004).

In short (and further discussed later in this chapter), there are four primary steps for a FRAM analysis depending on the purpose of the analysis (be it either incident investigation or risk assessment) and on the aim of each step.

- First of all, the functions required for a procedure to have a positive outcome are described in detail. That description of the functions is required to create the FRAM model.
- Secondly, each function's variability is described. In this step it is important to describe the potential variability of each function at first and then the actual variability the function was subject to in the instantiation being studied.
- The third step refers to the analysis of specific instantiations and how the combined variability of different functions may result in incidents.
- The fourth step consists of the actions suggested to manage the occurrences of variability of the necessary functions.

In the following paragraphs of this chapter, the steps are discussed in further detail and in regard to the application in this thesis.

3.2. Identification of Functions

The purpose of the first step is to describe the given procedure as a resultant of the functions needed in everyday work for it to succeed. In the words of Erik Hollnagel, the author of the "FRAM: the functional resonance analysis method", tasks and activities are two terms with significant meaning, different from one another. Task describes the work as it is imagined to be carried out by the designer, where activity is what is actually being done in real life situations like everyday work or an emergency response. The term procedure is used by the author of this thesis to refer to the higher function that is the target of the investigation. In the context of this thesis, the procedure is the emergency response on fire incidents onboard vessels.

In the cases of incident investigations, the functions are usually adequately described by the investigation report. Each step of the timeline of the events that happened helps identify the functions. This thesis creates a common framework for fire response procedures where the same essential functions are frequently encountered. Through this method of identification, the functions identified can be used in future investigations of similar events, regardless of different instantiations of the model. For tasks that may not be defined, but required for a risk assessment scenario, description through task analysis as described by the designer of by the authorities is incorporated.

In the context of FRAM, each function can be described by six features or aspects. The following table offers a description of these six elements:

Table 4 Six features/aspects of FRAM

Inputs (I)	The input needed to perform the function. Gets either processed or/and transformed or initiates the function
Outputs(O)	The product of the function. Can either be a change in state or of quality of the input.
Resources (R)	Needed during the execution of the function. May be consumed to produce the output
Controls/constraints (C)	The supervision of the function. Can be either another function or a regulation, procedure or restriction

Preconditions (P)	Need to be provided before the function is performed (e.g. hardware, energy, manpower)
Time (T)	Time related constrains that sets restrictions for the function. Starting time, end time and duration for instance.

After being described, the functions are represented in a graph in form of a snowflake. These "snowflakes" are necessary for the complete graphical representation of each instantiation. In the context of this thesis, these graphical representations and, hence, the function they describe are kept track as data for future incidents that involve the same functions.

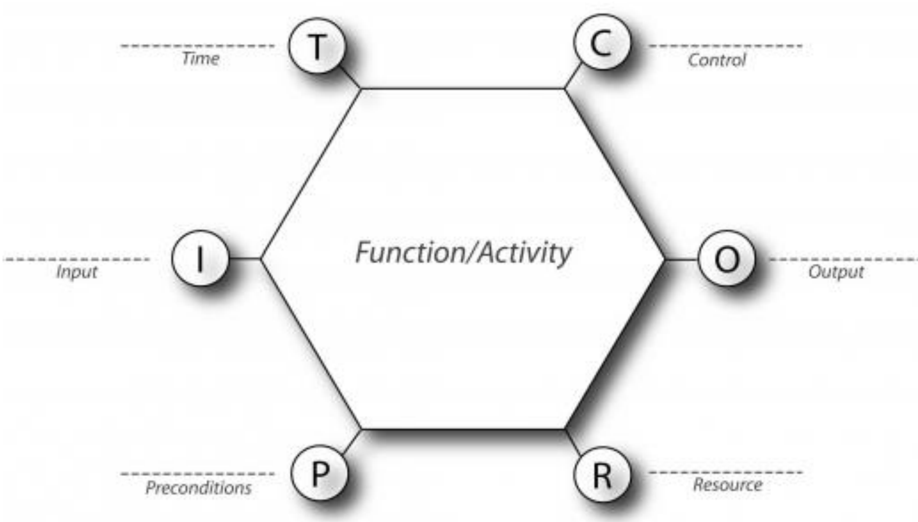

Figure 1: The FRAM "Snowflake"

It is also important to define when a function starts or stops. Referring to the description of the functions there are four ways to initiate or terminate a function.

Table 5 Ways to initiate or terminate a function

A change in the input indicating a change in system state.
A temporal constriction, either absolute or relative to another function being carried out.
A control relation, as is "sound the alarm" from a technical perspective when temperatures reach 150 degrees.
A change in the preconditions or the resources.

Other important characterizations of the functions are of temporal and of relative importance. The time functions are carried out relative to other functions describe them as upstream or downstream functions. This is of importance when describing an instantiation of the model, where the researcher needs to describe the queue in which the functions take place. The relative importance of the functions characterizes them as foreground functions, background functions and performance shaping factors. Foreground functions refer to the functions that are being analyzed or assessed. Background functions refer to the functions that shape or are needed for the working environment.

The essential system functions and components are identified through a number of investigative reports on fire incidents onboard. Incorporating the judgment of experts in the subject of firefighting onboard, professional trainers for crews, the essential functions are described and understood in detail .(Hollnagel, 2004).

3.3. Variability of the functions

Risk assessments based on the FRAM are based on functional resonance and are not constrained by pre-defined relations. FRAM views incidents as concurrencies of variability and does not make assessments on individual failures. The requirements for the application of the method are the potential and actual variability for the task or activity respectively. It is important to recognize when and how the variability may express itself and how this variability affects variability in later functions.

Potential variability refers to the many ways a function may vary, where actual variability refers to the variability that is expected in the instantiation being studied. Both kinds of variability must be described for both background and foreground functions. It is also important for variability to be expressed from everyday variability factors as well as out-of-border variability, when unusual causes may apply.

This step is important in order to analyze the potential couplings that may arise and to express how variability in two different functions may resonate. For example, one function may also vary if the input is the output of a function that varies.

That being said, there are three main reasons for variability of a function:

Table 6 Main reasons for variability of a function

A kind of external variability derives from a change in the conditions the functions is being carried out such as changes in the work environment. This is described as external variability
Variability of an output may arise from the changes in the function itself. This kind of internal variability is due to the way the function is performed.
Also the variability may be the result of the variability of upstream functions, when either inputs, preconditions, resources, control or time may vary. The aforementioned couplings are the focus of functional resonance.

An important action in this step of the FRAM, indeed for this thesis, is the characterization according to their type. That is, technological functions, human functions and organizational functions. This thesis finds this categorization especially important since all functions must be available for reviewing. Technological functions describe functions carried out by various machinery. These include technologies for collecting, storing, processing, analyzing and transmitting data and are often automated processes. Human functions are the result of individual humans, or small groups of people. This category has the highest frequencies of variability with significant outcomes. Last but not least, organizational functions, carried out by large groups of people, are highly organized. The effects of the variations are large but usually are of large magnitude.

After describing the potential variability of the functions it is crucial to distinguish between internal and external variability. Internal variability in technological systems is well known and either purely mechanical or due to the wear of time. For humans, internal variability is a result of physiological factors (stress, fatigue) and psychological factors that affect the elements of the second chapter. For the FRAM perspective, organizational variability can express itself in many different ways. External variability on the other hand may be expressed in improper maintenance and extreme working conditions for technological systems. Human functions may be affected by external variability sourced in technological and organizational reasons. Lastly, organizational external variability is mainly influenced by environmental, physical and legislative factors.

These notes are necessary for the proper application of FRAM in the later cases.

While the potential variability refers to the possible outcomes of the varied functions, actual variability refers to what should be expected in a given case. The instantiations in FRAM (for example, an incident investigation) require the actual variability either in hindsight or expressed in a realistic way describing what would be expected under the real-life conditions of the case.

3.4. Functional Resonance

The third step of a FRAM model is to describe the functional resonance. The set of functions described in a FRAM model are able to create several couplings between them. This way, it is possible to describe only the potential performance variability. The instantiations on the other hand, create a concrete set of couplings for a given case (either assumed or actual) and for specific conditions. Therefore, the potential variability is assessed as to how it can lead to actual variability. However, describing the actual –or the potential for that matter- variability is not enough for a complete research. The most important aspect of the FRAM model is the ability to assess how variability from different functions may combine and how this can lead to functional resonance.

As discussed earlier, the way a function may vary can be the result of either the function itself or the conditions it was carried out. The variability of a function can also be due to couplings to upstream functions, where the output of an upstream function may vary and therefore affect the variability of a downstream function (where it is used as input, precondition, control, resource or time). In certain situations, functions may amplify or dampen the carried variability of an upstream function. If a function has such an effect, it should be noted for further investigation.

All dependencies, both intended and unintended should be defined in order to describe the functional resonance within a system. The function’s aspects, input, output, time, preconditions, control and resources must be matched to each other so the functions will be connected. It is important for the researcher to use proper naming among those functions for the connections to be used by the FRAM software and ultimately for the creation of a common framework that has functions ready and easy to use in future investigations or assessments. These couplings that will be created allow the researcher to analyze the possible aggregation of variability that is needed for unexpected outcomes. As noted in earlier chapters, rarely variability in a single function that is not carried out to downstream functions can single-handedly affect the performance of the whole system. The aggregated variability from different functions however can greatly vary the outcome leading to unexpected results.

The created connections also allow the researcher to visually observe the procedure and highlight how a component's variability can impact another function's performance variability. The graphical representation of the FRAM is helpful for the identification of dependencies and the identification of functional resonance.

3.5. Suggestions for improvement

The last step of the FRAM method is to propose ways the aforementioned variability is controlled wherever it is expected change the expected outcome. Amplifying effects of functions on variability from upstream functions and uncontrolled performance should be managed. In the cases that the performance variability leads to positive results, FRAM suggests the management of the functions to facilitate and enhance the outcome since the latter is desirable.

The purpose of FRAM is to describe how performance variability may occur in every-day work operations and how the effects of the variability may migrate and enhance the variability on later functions. After this analysis the potential hazardous areas of the system should be managed to reduce the occurrences of such events or to mitigate the damage of the varied total outcome of the procedure. This can either be done by:

Table 7 Ways to increase resilience of a system

Eliminating the hazards founds by removing or changing the involved components. This method may be effective for specific case scenarios but usually has sub marginal results in different occurrences.
Another used solution for improvement is **prevention**. Prevention refers to the addition of barriers and defenses that may have dampening effects of the variability not to spread or damage mitigating effects if variability comes out of the expected borders. It is crucial to be accompanied by trade off analysis since usually come with reductions in speed and performance of the whole procedures. It is within this thesis analysis to suggest preventive measures through functions that are not taxing to the procedures they are involved.
The next solution is **facilitation**. Facilitation may involve the redesign of the system so it is more user-friendly and aim to make the system less complex. There are a lot of similarities to the prevention method but in the case of facilitation, instead of reducing harmful occurrences the aim is to enhance positive ones.
Lastly, **protection** refers to the damage mitigating methods that are used mainly after the incident occurs. While protection is a reactive tool, it needs to be designed proactively. Since this thesis analyzes fire incidents, protection elements on procedures are the focus of our investigation.

FRAM proposes two additional solutions to the aforementioned. Monitoring and dampening. Monitoring requires an extensive understanding of the system, its components and the processes that are involved. The selection of indicators is for monitoring is a difficult procedure which FRAM aids by proper understanding of the functions within the system and the expression of variability amongst them. Hence, FRAM models are very useful for proposing indicators. Functions' variability is as mentioned before in this thesis due to internal, external factors and due to upstream-downstream couplings. In the latter case, the transferred variability can and should be managed to reduce the effects on downstream functions, while the downstream functions can, by themselves, have a dampening effect that decreases variability later on.

To effectively manage a system, proper knowledge of its components is not enough. The manager, whoever he may be, needs to be able to intervene in the process and develop the needed outcome.

3.6. The FRAM Model Visualizer

The FRAM Model Visualizer is a software tool that allows the researcher to automatically create the graphical representation of a FRAM model. The FRAM Model Visualizer was developed by Rees Hill and this contribution to the FRAMily was significant. The FRAM Model Visualizer is developed in adobe air platform and is free for use. It is important to present some key features of the software tool in order to comprehend the results in later chapters accurately. Since the FRAM analyses any incident from a systemic perspective, the visual representation is an important addition for the ease-of-use of the method. Through this research, the software tool was found especially helpful for the analysis of the complex socio-technical system, allowing for better comprehension of the instantiation. The graphical representation produced by the software tool was also useful as a reference point when needed reducing the total time needed.

The layout of the FRAM Model Visualizer consists of two pane areas. The left panel, called "The function pane", is the area where a function is described. All the aspects that were described earlier (Input, Output, Control, Time, Precondition, Resource) are in detail in the pane. The function pane also includes the name and a short description of the function if needed. The functions can be characterized as technological, human or organizational and the variability can be described and represented visually with a curved line inside the FRAM "snowflake".

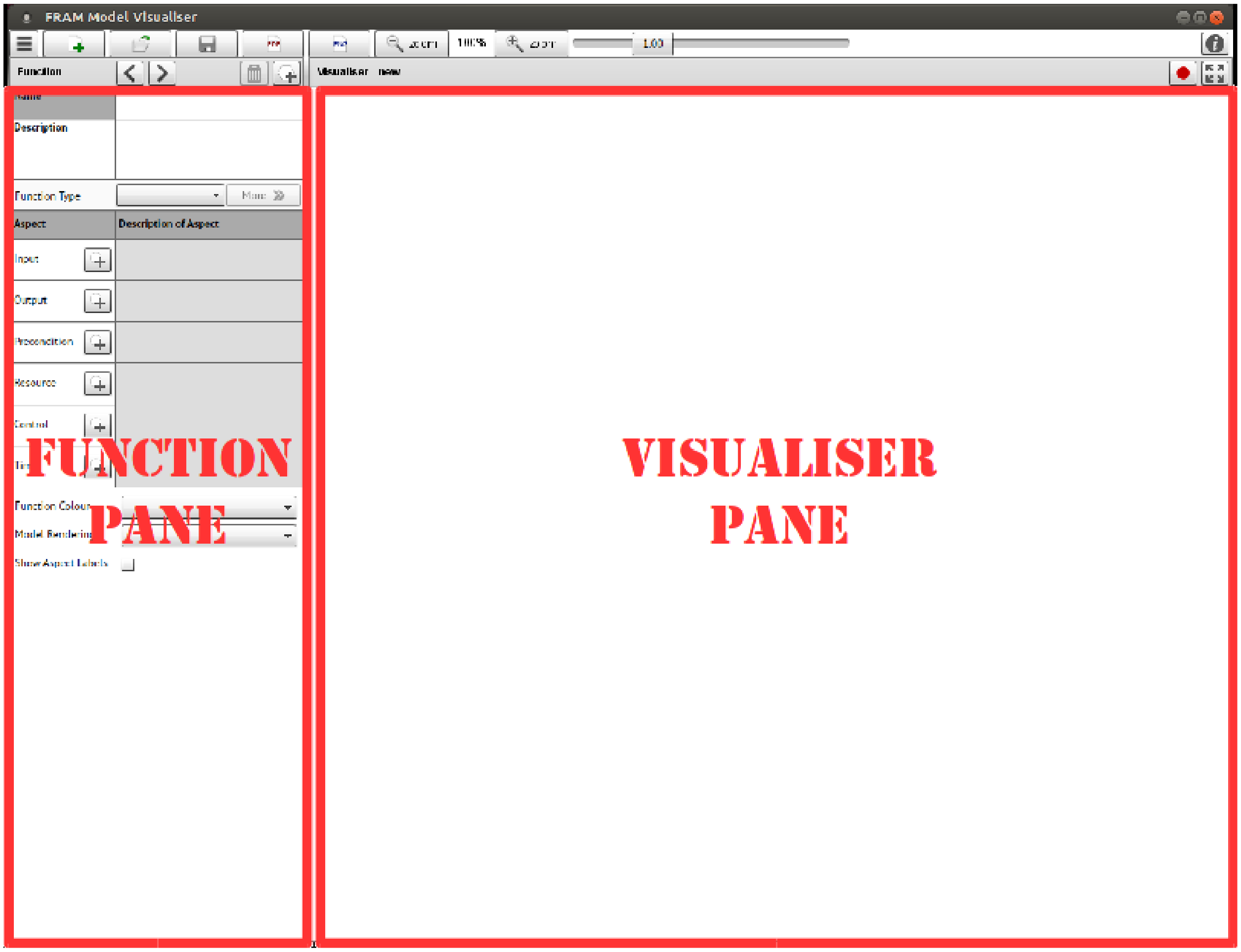

Figure 2 FRAM software main screen

The Visualizer pane is the area where all the functions are represented graphically. The software matches the states of all the Outputs defined by the user to create a web with the connections defined. For example, if an Output of a function is 'fire assessed' and the Input of a downstream function is 'fire assessed', the visualizer pane will create this connection with a curved line, with the state 'fire assessed' written clearly on the line. It is important to note that the state must have the exact same name on both functions and it is case-sensitive. Moreover, the variability of the function can be described for any function. Finally, the software tool includes some rendering options for different representations.

If the function in question is a **technological function** the table of variability is as follows:

Possible source of variability		Likelihood
Internal	Few, well known	Low
External	Maintenance, (mis)use	Low

Potential Output variability with regard to time	
Too early	Unlikely
On time	Normal, expected
Too late	Unlikely, but possible if software is involved
Not at all	Very unlikely (only in case of complete breakdown)

Potential Output variability with regard to precision	
Precise	Normal, expected
Acceptable	Unlikely
Imprecise	Unlikely

Figure3 Technological Function - Table of Variability

While, if the function is a **human function** the variability table is:

Possible source of variability		Likelihood
Internal	Very many, physiological and psychological	High frequency, large amplitude
External	Very many, social and organisational	High frequency, large amplitude

Potential Output variability with regard to time	
Too early	Possible (snap answer, serendipity)
On time	Possible, should be typical
Too late	Possible, more likely than too early
Not at all	Possible, to a lesser degree

Potential Output variability with regard to precision	
Precise	Possible, but unlikely
Acceptable	Typical
Imprecise	Possible, likely

Figure 4 Human Function - Table of Variability

Lastly, if the **function** in question is **organizational** the table is as follows:

Possible source of variability		Likelihood
Internal	Many, function specific and/or relating to 'culture'	Low frequency, large amplitude
External	Many, instrumental or 'culture'	Low frequency, large amplitude

Potential Output variability with regard to time	
Too early	Unlikely
On time	Likely
Too late	Possible
Not at all	Possible

Potential Output variability with regard to precision	
Precise	Unlikely
Acceptable	Possible
Imprecise	Likely

Figure 5 Organizational Function - Table of Variability

Both pop-up tables can be used to mark the variability of any function.

The FRAM Model Visualizer can export the function as they were described by the researcher in a .PDF file format and the graphical representation can be extracted as a .PNG file format with clear image sharpness.

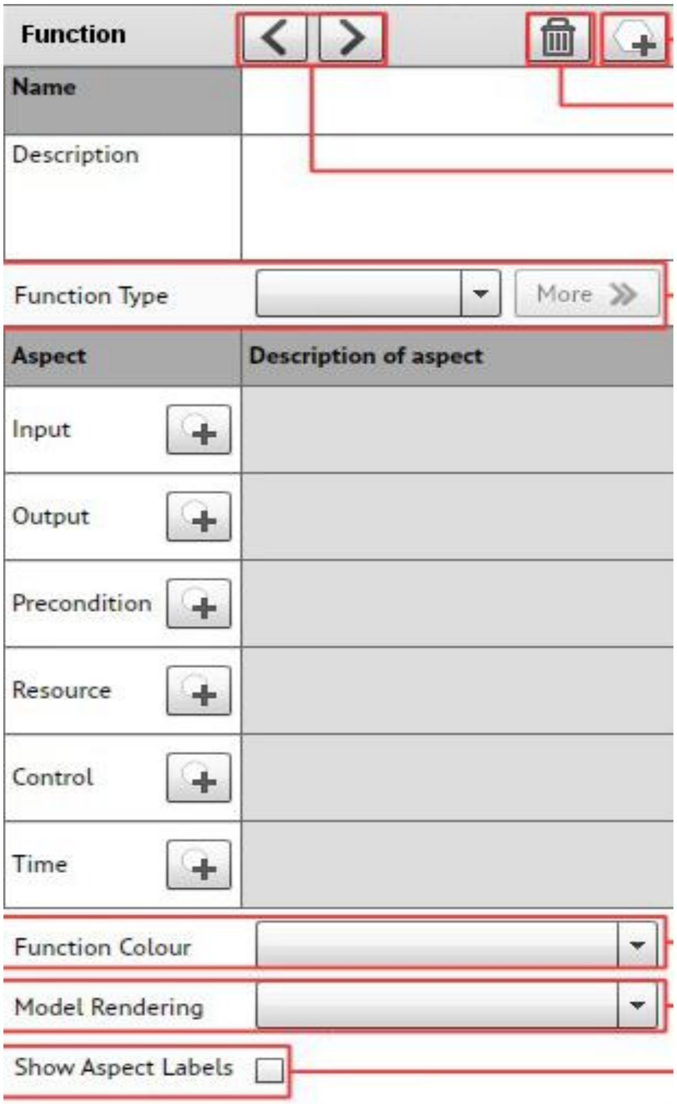

Figure 6 Function List on software

An additional capability of the software tool is to record preset sequences of events. This allows for clear understanding of the events that happen and how the couplings were created. This was not found useful by this thesis analysis and is only being mentioned in this paragraph.

4. State-of-the-Art

A growing body of scientists (Amalberti, 2001; Dekker, 2004; Hollnagel, 2004) suggest that there is indeed a need for new incident models in order to understand concepts such as “incident” and “incident” and their effects on safety –as an emergent property of system. Furthermore, turning away from a human-centred perspective that focuses on single events and human errors, to a system-centred perspective (Holden, 2009) will provide an in-depth understanding of incident causes and why incidents occur, giving us the possibility to effectively and proactively manage safety.

During recent years, systemic incident analysis methods have been developed (Leveson, Dulac, Marais, & Carroll, 2009; Stoop & Dekker, 2009).

The method for modelling complex socio-technical systems used in the course of this study is the Functional Resonance Analysis Method, in the following referred to as the FRAM. This method will be discussed in detail with a dedicated chapter.

In addition to the mentioned ongoing research, several organizations are funding actions that investigate maritime safety and safety in transportation as the European Union (EU), European Research Council (ERC), European Maritime Safety Organization (EMSA) and the IMO. Indicative projects that deliver(ed) tangible results that increase the level of safety onboard ships are:

Table 8 Ongoing research on maritime safety

eVACUATE	A holistic scenario – independent, situation-awareness and guidance System for sustaining the Active Evacuation Route for large Crowds
HOLISHIP	HOLIstic optimization of SHIP design and operation for life cycle
SAFENVSHIP	Develop, evaluate and validate methodologies and tools for design of the next generation cruise/ferry ships related to: 1. Safety: fire protection, structural (hydroelasticity), wind effects/evaluation. 2. Environment: clean sea/air.

LYNCEUS2MARKET	On-board and overboard people localization, person activity monitoring, real-time disaster escalation monitoring and adaptive decision support
LETS-CROWD	Real time crowd behaviour forecasting models inevacuation strategies
FLOODSTAND	Flooding sumulation tools, ship response and rescue process modelling

These funded projects are a sample of the ongoing research in the field of maritime safety. Maritime safety consists a complex challenge that needs to be assessed through different routes and methodologies given its highly non-deterministic nature. FRAM offers an alternative solution of great value in tackling such challenges via a different perspective.

The following is a list of academic papers related to this study with a brief summary with more detail in the items of this study’s focus. It is important to emphasize the areas that these methods have already been used for a better understanding of this thesis perspective and goals.

Resilience Assessment Based on Models of Functional Resonance:

This paper examines process-based methods for the assessment of Resilience. This need is due to the fact that sociotechnical systems are highly complex with little importance given on system outputs because of their inability to capture the dynamics within the system. The authors of this paper explore the potential of FRAM to evaluate five important resilience characteristics. There are buffering capacity, flexibility, margin, tolerance and cross-scale interactions. The case of Alaska Airlines flight 261 incident was studied under the prism of FRAM and the model was evaluated for resilience assessment potential. In serendipity, during the research and in search for the answers the authors challenged the definition of these characteristics. (Rogier Woltjer, 2017)

The case of Herald of Free Enterprise:

The tragic incident of the Roll on/Roll off Ferry Herald of Free Enterprise lead to a human-centered view on the investigation of its causes. The formal investigation report concluded that both the crewmembers and the shipping company were responsible for the incident. The perspective that views incidents as the outcome of a chain of events leading to an unwanted consequence is researched for more than 20 years. This paper attempts to reanalyze this incident from a systemic point of view utilizing FRAM to identify what may have caused the ship to capsize. High focus is given on whether incident analysis can help proactively improve the safe operation of ships.

It was the first time an incident investigation took into account the decisions made on shore that affected the safe operation at the vessel and held (partly) the shipping company accountable.

This article reanalyses the incident of the Herald of Free Enterprise. The analysis is built solely upon the formal investigation report (Department of Transport, 1987) using the functional resonance analysis method (FRAM) developed by Hollnagel (2004).

The first step of the analysis was to identify the 34 functions derived from the report and then described to sex characteristics. After the functions had been described by their characteristics, the potential variability for each function was determined with the help of the 11 CPCs, each representing aspects of human, technological and organizational context in which the function is executed. Later, the functions were graphically represented and connected based on their relation to each other. Based on the model, suggestions for countermeasures were formulated. The paper could not provide new conclusion on the incident's causes but provided deeper understanding of FRAM and its potential. (Gesa Praetorius, Monica Lundh et Margareta Lützhöft, 2017)

Resilience Engineering Approach to Safety Assessment: An Application of FRAM for the MSAW system:

The Minimum Safety Altitude Warning system (MSAW) alerts the Air Traffic Controller (ATCO) of potential Controlled Flight into Terrain and Controlled Flight into Obstacles and provides with adequate time and instructions to be issued to the pilot. This study describes a safety assessment of the MSAW. Beginning with identification and description of the functions using FRAM, the authors evaluate the introduction of MSAW into an existing ATCO FRAM model. The evaluation is based on functions' performance variability and on the occurrence of unexpected combinations. MSAW is a system designed to run on the background, not disrupting existing ATC processes and alerting (with sufficient time) serious path deviations and Controlled Flight into Terrain or Obstacle (Luigi Macchi, Erik Hollnagel and Jorg Leonhard, 2016). This paper analyses the system functions to create the FRAM model. Then, several scenarios are created and each function's variability is evaluated including technical and human factors. The risk assessment is based on the performance of the complex system that takes into account the interactions between functions.

Analysis of interdependencies within the firefighting function on an off shore platform:

This thesis challenges the energy-barrier philosophy as the ruling principle in offshore safety. The issue identified in this philosophy is the paradoxical increased complexity and the neglect on the complex interactions within the system. The different method suggested by the author to study interdependencies in an offshore platform barrier system is FRAM, and it is used for the analysis of the firefighting function on an offshore platform. The two major parts of this project are a) to identify and describe the functions and to b) analyze the variability and functional resonance in former model. This paper both access whether interdependencies in barrier system matters and also apply a method to interpret interdependencies in a barrier system and evaluate the method used. Part of the extensive system is only taken into account due to complexity. The use of FRAM is detailed and the countermeasures are evaluated. FRAM analysis illustrated the interdependencies on the system during one risk assessment scenario and two events when happening. It is important to note that this thesis opened ways for future research as it was discussed. (Jens Ehman, 2013)

Model-Based Safety Assessment using FRAM for complex systems:

This paper examines the use of FRAM, as a new methodology that values the interactions within complex systems instead of the usual couplings provided by other methods. A model based safety assessment using FRAM is proposed to identify hazards and analyze incident scenarios. The case of landing process of an airplane is demonstrated as an example of the model's use. (Q. Yang & J. Tian, 2015)

Automation of the FRAM method for the purpose of hazard analysis:

This research comes from Slovenia Control to examine FRAM as an automated complimentary tool for safety assessment. It is noted, that the only acceptable mean of compliance to ESARR4 as of today is SAM, a tool most suitable for hardware changes from the design process. The goal of this study is to come up with an algorithm to describe FRAM as a finite state machine (M.Pielick, Slovenia Control Ltd., Zgornji Brnik, Slovenia & prof.M.Mraz, PhD, Faculty of Computer and Information Science University of Ljubljana, Slovenia, 2016). Here, simulation clarifies the consequences of the relations that are described in the FRAM model, which can then be tested against observations in the real world. Simple and elaborate descriptive data capture most consequences and are able to refine their description. The potential variability and the description of performance variability attempts to quantify FRAM without assigning numerical values to a performance variability state but with discrete probability distribution functions. The authors examine assigning each function with weight of significance and a specific index to represent damping or amplifying effect of each coupling. The solution of calculated instantiations (where FRAM is interpreted as a network or graph) could meet the practical demand for quantitative results.

Functional modeling for risk assessment of automation in a changing air traffic management environment:

This research examines the effects on the automation proposal of the ERASMUS project. The ERASMUS project proposes a slight adjustment to the aircraft speed to avoid conflicts and the argument to inform the pilot or adjust automatically is examined in this paper. Various instantiations of a partial model resulting by the application of FRAM are presented to evaluate the impact of the ERASMUS application on controller and pilot. The motivation for this paper is the usually problematic application of automation in a complex system. Through observations, interview and the aggregation of identified functions in published models of en route control, the controller functions are identified and the FRAM model is completed after the usual steps of the method. (R. Woltjer and E. Hollnagel, 2008)

Decision support analysis for safety control in complex project environment based on Bayesian Networks:

This paper suggests a systemic decision support model based on Bayesian Networks for safety control in dynamic complex project environments. Firstly, expert knowledge and training data are integrated to produce a reliable and adaptable model. Then, Model Bias and Model Accuracy assess the effectiveness of the Network by comparing the results with actual observations. Finally, the safety control process is extended to the entire life cycle of the system. The study provides a supportive tool for decision makers taking ground settlement during Wuhan Changjiang Metro Shield Tunnel Construction as a case study by demonstrating the feasibility of a BN model and its potential. (Limao Zhang, Xianguo Wu, Lieyun Ding, Miroslaw J. Skibniewski, Y.Yan, 2012)

Safety is an emergent property: Illustrating functional resonance in Air Traffic Management with formal verification:

The inspiration of this paper is the frequent investigator incapability to explain how emergent phenomena appear and develop. It is considered that functional resonance is insufficient in explaining how the resonance occurs in certain scenarios. Also, it is considered that the methods that utilize functional resonance are limited regarding hazard identification. The paper attempts, with the use of FRAM to develop a comprehensive approach by formal verification tool SPIN. The FRAM is selected because of the ability to monitor system functions. The approach is applied to Air Traffic Management system where Minimum Safe Altitude Warning is introduced. The aim is to illustrate how minor variability of different functions can result in significant effects to the performance of the aforementioned system. (Qibo Yang, Jin Tian, Tingdi Zhao, 2017)

Developing a Risk-Based Approach for Optimizing Human Reliability Assessment in an Offshore Operation:

This paper estimates the probability of system failure due to human error in light structure lift in sea. The authors select the FRAM to create the non-linear socio-technical function network of this procedure. The FRAM model is integrated with Success Likelihood Index Method (SLIM) considering human errors. The study quantifies the qualification process of the FRAM and applies in an offshore oil platform. The Event Tree is conducted to assess the consequences afterwards indicating that the integration of the mentioned tools have application in the offshore platform industry. (Ahmad Bahoo Toroody, Mohammad Mahdi Abaiee, Reza Gholamnia, Mohammad Bahoo Torody, Nastaran Hekmat Nejad, 2016)

A white paper on resilience engineering for Air Traffic Control:

In this white paper the authors examine the value of resilience engineering to provide assurance of the Air Traffic Management safety. After a complete description of the usefulness of performance variability and the facilitation of resilience engineering in Air Traffic Management System, the paper suggests that more effort should be given on developing a more complete model for resilience engineering application. The resilience engineering approach needs to mature and future research is required. (European Organization for the Safety of Air Navigation (EUROCONTROL), 2009)

An application of the Functional Resonance Analysis Method (FRAM) to Risk Assessment of Organizational Change:

This study aims to examine an alternative approach to risk assessment of organizational changes, utilizing the principles of resilience engineering. Considering that the current approaches accept risk as a result of failure or malfunction, the application of the Functional Resonance Analysis Method is selected. Resilience engineering proposes that failures are the result of the same variations that are necessary for success (Erik Hollnagel, 2013). The analysis via this approach offers a new perspective of the system from a systemic point of view.

Intermediate report of MoReMO. Modeling Resilience for Maintenance and Outage:

During this study the FRAM is used for the safety analysis of nuclear power plants. Nuclear power plants are an organization that is subject to large modification projects and increased need for more efficient safety procedures. The systemic approach is utilized to develop and test models to analyze safe performance in critical activities during routine operations (Oedewald P., Macchi L., Axelsson C., Eirtheim M.H.R., 2012). Integrating Organizational Core Task modeling, Efficiency Thoroughness Trade-Off and Work Practice and Culture Characterization with the FRAM the paper provides significant insight on understanding everyday work practices. The common grounds of the two industries are noticeable with the need of improved safety system and the presence of high risk hazards.

A Monte Carlo evolution of the Functional Resonance Analysis Method (FRAM) to assess performance variability in complex systems:

This paper integrates the FRAM with Monte Carlo evaluation to apply to the Air Traffic Management (ATM) system in order to examine the technological, human and organizational components of the system. The ATM is chosen as a high risk environment with significant socio-technical interactions. The innovative model attempts to quantify critical points in Monte Carlo simulation and applies to the ATM process.

The FRAM is also used in workplace safety (Amorim and Pereira, 2015) , in medical science (Pereira, 2013; Clay-Williams et al., 2015; Alm and Woltjer, 2010),in transportation management (Belmonte et al.,2011; Praetorious et al.,2015), and in oil exploitation (Aguilera et al.,2016).

The value of this literature review is to present some examples of the application of the method in different industries. The purpose of this study is to evaluate the use of FRAM in fire incident on board vessel. Therefore, the applications that are already in place assist in developing a more complete model for the system in this thesis. This review offered valuable insight on the use of the model and on the needs for future research are proposed by the aforementioned authors.

5. Instantiations of two cases

In this chapter, two separate cases of marine incidents are examined with the analysis of functional resonance. The aim of this chapter is to attempt to make recommendations that derive from the functional analysis of the events, utilizing the Functional Resonance Analysis Method.

The incidents are first described as happened. The description is trusted to the official investigations' reports. The focus of the description is on one hand to provide a wider perception of the event and on the other to comprehensively describe the events as they happened.

Afterwards, the functions necessary for the application of FRAM are described. The description is based on the functions identified from the event as happened as this is considered to be a realistic response to the presented and other similar hazards. To identification, as FRAM instructs, is a description of the function with the respected aspects. The aspects are described in detail as they were selected. The analysis in this thesis describes an increased amount of functions to examine the value of this approach. It is believed that there is a limit to the detail of the description as more functions can become redundant. The data used for the course of this paper comes from UK's Marine Incident Investigation Branch (MAIB).

Following the descriptions of the functions, a complete analysis of the variability observed is attempted. The variability of the Output due to internal variability and the upstream-downstream variability observed is analysed and presented in a table, as the application of FRAM instructs.

The model is then presented in graphical representation form extracted from the FRAM Model Visualizer, the provided software for the ease of use of the FRAM. The analysis of the functions' variability and the graphical representation provided data on functional resonance which are described in later paragraphs.

The investigation terminates when suggestions are made using the principles of resilience engineering. The aim is to increase the responsiveness of the system in similar incidents rather than preventing the incident from occurring. Even though such an approach certainly has value, the approach of this thesis is focused on systemic analysis of the functions. In cases were functions were added as a suggestion, the updated graphical representation of the system is presented. Through systemic analysis of the socio-technical system the human liability is given focus.

5.1. Case “Commodore Clipper”

Description of the Event

A fire occurred on 16 June 2010 on the Commodore Clipper while on passage from Jersex to Portsmouth. The fire was caused by the electrical supply of a refrigerated unit because of an arc, created by high resistance on the cables. Besides the actual reasons of the ignition, it is worth noticing that crew members on watch, bypassed the alarm several times because they were thought as false (perception that was further supported by rushed on-spot inspection for smoke). Also, the afterwards procedures were challenged by a reported confusion about jurisdiction and responsibilities issues that further delayed the response.

CCTV image of the main vehicle deck became hazy. Shortly afterwards, the machinery control alarm sounded indicating an earth fault at the bus-tie break that connected two electrical circuits. Meanwhile, the third engineer on watch heard a noise. After a short period of time the CCTV showed much darkened images of the main vehicle deck. The smoke alarm activated indicating smoke in the same compartment. After 30 seconds, nearby fire sensors detected fire. The third engineer then reported the alarm to the bridge where the second officer was on duty. This communication was made via telephone. The second officer instructed a lookout to confirm the fire in the main vehicle deck via VHF. The lookout first visited the passenger restaurant where two crew members confirmed the smell of smoke. Meanwhile, the third engineer bypassed the alarms for a total of 81 times since he believed there was a malfunction in the detection system. Thus, he called the electrical fitter to check the fire detection system. The alarm was reset with additional sensors indicating fire after rebooting. The report to the bridge from the third engineer confirmed no fire. The second officer received eight VHF calls that were incomprehensible since it was known that the portable VHF was in bad condition. The electrical fitter encountered smoke when trying to enter the main vehicle deck and retreated. He reported to the third engineer and later to the bridge and the two men isolated the power supplies to the refrigerated units. The third engineer initiated the auxiliary generator to take the load off the shaft generator. The CCTV images continued to get increasingly darker with little to no visibility. The ventilation fans were stopped automatically as they were designed. Another alarm for a faulty earth of a bus-tie break sounded. Meanwhile, the lookout confirmed the fire. The chief engineer decided to check for himself and sounded the alarm and the general emergency signal. He later checked the ventilation fans on the vehicle decks to be closed and initiated the drenching system. Shortly after, the water leakage alarm sounded indicating water started to drain. The hotel staff checked each cabin and directed the passengers to the assembly stations. The crew mustered in the one of the required stations since the second one was unreachable. The lookout, with EECB entered the vehicle deck and confirmed and assessed the magnitude and position of the fire. The master then reported to coast with no distress signal. Coast requested the Marine Incident Response Group (MIRG) to standby as well as experienced firefighters (HFRS) if needed onboard. The chief engineer requested the bridge to send someone to close the exhaust dampers manually and two crew members succeeded. Then, the chief officer ordered boundary cooling from the upper deck where smoke and high temperatures were recorded. This was done via the drenching system and fire hoses. The CCTV showed large clouds of steam in the compartment and the crew were unable to attack the fire because the hoses were reported hot and the maneuverability was limited. The master requested help via helicopter and it was confirmed. The vessel maintained normal course at full speed through the incident in an attempt to reach the port. There were delays because of misconceptions on whether help was needed or discussed as an option. The fire was contained. The water created serious list and the drenching system was turned off and on to tackle this with success. The steering pump later failed and the rudder turned. Unable to control the vessel the master requested assistance with a tug boat. Smoke was later detected in the accommodation through a large green staircase that fed air to the fire. The fire screen doors were closed and all the drenchers were activated. The vessel had lost the bow thrusters and the steering gear, with no power to neither anchor nor maneuver.

Identification of the functions

The construction of the instantiation is independent of the starting point and FRAM does not provide guidance for the selection of the starting point. Since this thesis focus is incidents on board vessels, it is vital to define the events that signalled the initiation of the system's response as well as boundaries to the analysis. Thus, the vessels evacuation was considered the final function. However, it is important to note that the instantiation is complete with the fire response since the initiation through the flooding caused by the drenching system and the damages to the machinery until the communication with authorities throughout the incident. It must be noted that the function identification process is not linear but in this thesis best efforts are presented in the most understandable mean possible.

Name of Function	Evacuate Ship
Description	
Aspect	Description of Aspect
Input	Vessel Arrived at Port
Output	N/A (Not Applicable)
Precondition	Passengers Assembled
Resource	N/A
Control	Fire Contained
Time	N/A

Table 9 Function - Evacuate Ship

In order to evacuate the ship properly in this incident, the vessel must arrive at the port. Thus, the Input of the "Evacuate Ship" described in the table above is the state "Vessel Arrived at Port". This function has Control the "Fire Contained" state since the function may not performed as intended if the fire is not contained and passengers are trapped or unable to disembark. The function "Contain Fire" is identified. The Input state can be achieved through two different means. The first is for the vessel to maintain course and anchor safely on port. Thus, the function "Maintain Course" is identified. Also, the function "Tug vessel" is identified in hindsight to the incident since the vessel arrived at port towed. The precondition for this function to perform as intended is to have the passengers assembled. Thus the function "Assemble Passengers" is identified but discussed later.

Name of Function	Maintain Course
Description	
Aspect	Description of Aspect
Input	N/A
Output	Vessel Arrived at Port
Precondition	Bow Thrusters Activated
	List Maintained
Resource	N/A
Control	N/A

Time	N/A

Table 10 Function - Maintain Course

The output of the function "Maintain Course" is to arrive at the port. For this action to complete, again in hindsight in order to omit the factors that did not contribute to the incident, two preconditions are identified. First the bow thrusters must be activated and so the function "Activate Bow Thrusters" is identified. Also, the function "Maintain list" is required as a precondition for this function to perform as intended.

Name of Function	Maintain List
Description	
Aspect	Description of Aspect
Input	N/A
Output	List Maintained
Precondition	Water Drained
Resource	N/A
Control	N/A
Time	N/A

Table 11 Function - Maintain List

The output of the function "Maintain List" is to have the necessary list for seakeeping. The precondition of this function to perform as intended is to have a well-balanced cargo and no free surface effect from the water used to attack the fire. Thus, the water must be drained and a new function is identified, "Drain water".

Name of Function	Activate Bow Thrusters
Description	The bow thrusters can be activated both remotely and manually.
Aspect	Description of Aspect
Input	N/A
Output	Bow Thrusters Activated
Precondition	Power Provided
Resource	N/A

Control	N/A
Time	N/A

Table 12 Function - Activate Bow Thrusters

The output of the function "Activate Bow Thrusters" is to have the vessel's bow thrusters ready and functional for manoeuvring. The necessary precondition for this function is to have power supplied to the thrusters regardless of manual or remote use. Thus the function "Power Provided" is identified.

Name of Function	Provide Power
Description	
Aspect	Description of Aspect
Input	N/A
Output	Power Provided
Precondition	N/A
Resource	Backup Generator Initiated
Control	N/A
Time	N/A

Table 13 Function - Provide Power

The obvious output of the function "Provide Power" is to have power provided where needed. In case of a generator failure, there is a backup generator that needs to be initiated to support the electrical circuit. The function "Initiate Backup Generator" is identified but will be described later.

Name of Function	Tug Vessel
Description	
Aspect	Description of Aspect
Input	Tug Boat Sent
Output	Vessel Arrived at Port
Precondition	N/A
Resource	N/A
Control	Tug Boat Requested

Time	N/A

Table 14 Function - Tug Vessel

The function "Tug vessel" has the output of the vessel being towed to port. In order for this function to perform efficiently the tug boat must be requested by the vessel's master and sent by port authorities. The input to initiate the function is to send the Tug board under authorities' orders but since approval is needed by the vessel's master the function has control "Tug boat requested" in the sense of a formal request.

Name of Function	Contain Fire
Description	
Aspect	Description of Aspect
Input	Water Applied to Fire
Output	Fire Contained
Precondition	Fire Suffocated
Resource	N/A
Control	Boundaries Cooled
Time	N/A

Table 15 Function - Contain Fire

This higher function is needed to contain the fire, mitigating the spread and ensuring the safety of the passengers. As discussed in earlier chapters, the goal of the emergency response is primarily to contain the fire until external help arrives. This function could be the end result of the analysis if the focus was solely on the fire emergency response of the system. Since the socio-technical system and the result of the incident greatly depended on the actions taken ashore and the fact that the containment of the fire resulted in excess weight from water applied to the fire. The input of the function "Contain Fire" is to have water applied to the fire. The precondition is to have the fire deprived of air and the function is maintained only if the boundaries are cooled. Thus, the functions "Cut Air Supply", "Cool Boundaries" are identified. The input "water applied to fire" can be obtained from two functions. At first, the fire party of the vessel must apply water to the fire, hence the function "Fight Fire Manually" is identified. Since, the fire party is not as qualified as experienced fire-fighters from ashore, the function

“Send Helicopter Aid” is identified, referring to the assistance of experienced fire-fighters from ashore.

Name of Function	Cut Air Supply
Description	In order to successfully contain the fire, air supply to the compartment must be reduced
Aspect	Description of Aspect
Input	Fire Doors Closed
Output	Fire Suffocated
Precondition	Ventilation Stopped
Resource	N/A
Control	N/A
Time	N/A

Table 16 Function - Cut Air supply

The Output of the function “Cut Air Supply” is to have the fire deprived of oxygen. In order to perform as intended, the fire screen doors must be closed, and this is done by the fire party. Hence, the already identified function “Fight Fire Manually” will have this state as an Output. Also, the ventilation must be stopped as a precondition, since constant air supply from the ductings can negatively affect performance. The ventilation is automatically stopped when smoke is detected and performed as intended. Thus, the function “Automatically Detect Smoke” is identified.

Name of Function	Automatically Detect Smoke
Description	Smoke detectors
Aspect	Description of Aspect
Input	N/A
Output	Smoke Detected Automatically
	Ventilation Stopped
Precondition	N/A
Resource	N/A
Control	N/A

Time	N/A

Table 17 Function - Automatically Detect Smoke

The Output of the function "Automatically detect smoke" is both to automatically close the ventilation in the compartment and to alert crew members on watch that smoke was detected automatically. The latter Output will be the Input in later functions. The system is automatic and the possible input is the smoke from the fire that constitutes the starting point for this instantiation.

Name of Function	Fight Fire Manually
Description	
Aspect	Description of Aspect
Input	Fire Confirmed
Output	Fire Doors Closed
	Water Applied to Boundaries
	Water Applied to Fire
Precondition	Power Supply Isolated
	Fire Assessed
Resource	Firefighting Equipment Provided
Control	N/A
Time	Fire Party Mustered

Table 18 Function - Fight Fire Manually

The Outcomes of the function "Fight Fire Manually" are both to apply water to the fire and to have the fire screen doors closed. The first Outcome will come useful in later descriptions. The Input for this function to initiate is to have the fire confirmed, thus the function "Confirm Fire" is identified. Another outcome of the manual fire fighting is to apply water on boundaries needed later for boundary cooling. The preconditions for this function to perform as intended are to have the power supply near the fire isolated and to have the fire assessed in order for the fire party to have situational awareness. Thus the functions "Isolate Power Supply" and "Confirm Fire" (also referring to assessing the magnitude) are identified. The resource of this function is to have the fire fighting equipment provided for the attack. Thus, the function "Provide Fire

Fighting Equipment" is identified. Also, the time the function initiates is depended on the time the fire party is mustered. Thus, the function "Sound Crew Emergency Alarm" is identified.

Name of Function	Isolate Power Supply
Description	
Aspect	Description of Aspect
Input	Electrical Fitter Summoned
Output	Power Supply Isolated
Precondition	N/A
Resource	N/A
Control	N/A
Time	N/A

Table 19 Function - Isolate Power Supply

The power supply is isolated under the watch of either the electrical fitter or an engineer. In this instantiation the electrical fitter was summoned to isolate the power supply when the alarm was interpreted, thus the function "Interpret Alarm" is identified.

Name of Function	Provide Firefighting Equipment
Description	
Aspect	Description of Aspect
Input	N/A
Output	Firefighting Equipment Provided
Precondition	N/A
Resource	N/A
Control	N/A
Time	N/A

Table 20 Function - Provide Firefighting Equipment

The Outcome of this background function is to provide the necessary equipment for the fire fighting efforts.

Name of Function	Confirm Fire
Description	
Aspect	Description of Aspect
Input	Lookout Sent
	Engineer on watch sent
Output	Fire Assessed
	Fire Confirmed
Precondition	N/A
Resource	Firefighting Equipment Provided
Control	N/A
Time	N/A

Table 21 Function - Confirm Fire

The Outcome of the function "Confirm Fire" is to both confirm the existence of the fire and assess the magnitude of the fire. In order for this function to perform as intended a lookout was sent to the compartments where the alarms were indicating fire. Since the lookout was sent to confirm from the bridge, the function "Supervise from Bridge" is identified. Also, as a second input to this function, an engineer was sent to assess the fire again. The engineer was sent there in order to assess the damage and assist his decision making, as a result of the interpretation of the alarm that was described in the "Interpret Alarm" function. The resources for this function is to have fire fighting equipment provided for the lookout and the engineer in order to come as close as possible and identify the extent of the damage accurately. This resource is provided by the earlier function "Provide Fire Fighting Equipment"

Name of Function	Interpret Alarm
Description	Crew member on watch evaluates the alarm signal
Aspect	Description of Aspect
Input	Smoke Detected Automatically
	Bus-Tie Break Alarm
	Fire Detected Automatically
Output	Report to Bridge

	Electrical Fitter Summoned
	Engineer on watch sent
Precondition	N/A
Resource	N/A
Control	N/A
Time	N/A

Table 22 Function - Interpret Alarm

The Output of the function “Interpret Alarm” is to report the alarms to the bridge, to summon the electrical fitter since electrical circuits alarms were also sounded, and to send the engineer on watch to confirm and assess the fire. The Inputs of this function was the sound of the smoke detection system, a bus-tie alarm and the fire sensors alarming. Thus the functions “Automatically Detect Fire” and “Automatically Monitor Electrical Circuits” are identified. The Function “Automatically Detect Smoke” is already identified.

Name of Function	Automatically Monitor Electrical Circuits
Description	The vessel supplied refrigerated units with electricity
Aspect	Description of Aspect
Input	N/A
Output	Bus-Tie Break Alarm
Precondition	N/A
Resource	N/A
Control	N/A
Time	N/A

Table 23 Function - Automatically Monitor Electrical Circuits

The Output in this instantiation of this technological function is to alert of earth faults in bus-tie break alarms. The input is not described since the detection of the fault that is our starting point caused the alarm.

Name of Function	Automatically Detect Fire
Description	Via Fire Sensors
Aspect	Description of Aspect
Input	N/A
Output	Fire Detected Automatically
Precondition	N/A
Resource	N/A
Control	N/A
Time	N/A

Table 24 Function - Automatically Detect Fire

The Outcome of the function “Automatically Detect Fire” is to detect the fire via the fire sensors. When the fire sensors detected the heat from the fire, that is our starting event, the fire detection alarm was sounded.

Name of Function	Initiate Backup Generator
Description	
Aspect	Description of Aspect
Input	Electrical Fitter Summoned
Output	Backup Generator Initiated
Precondition	N/A
Resource	N/A
Control	N/A
Time	N/A

Table 25 Function - Initate Backup Generator

The Outcome of this function is to have the backup generator initiated if needed. This function was carried out by the electrical fitter after the interpretation of the alarms. The function “Interpret Alarm” is identified again.

Name of Function	Sound Crew Emergency Alarm
Description	
Aspect	Description of Aspect
Input	N/A
Output	Fire Party Mustered
	Evacuate Team Mustered
Precondition	Power Provided
Resource	N/A
Control	N/A
Time	Fire Confirmed

Table 26 Function - Sound Crew Emergency Alarm

The Outputs of this function are to have the fire party as well as the evacuate team mustered for the needed later functions. The time this function is initiated is depended on the time the fire was confirmed and assessed by the already identified "Confirm Fire" function. The precondition for this function is to have power provided by the "Provide Power" function identified earlier.

Name of Function	Cool Boundaries
Description	
Aspect	Description of Aspect
Input	Water Applied to Boundaries
Output	Boundaries Cooled
Precondition	N/A
Resource	N/A
Control	N/A
Time	N/A

Table 27 Function - Cool Boundaries

The Outcome of the function "Cool Boundaries" is to have the boundaries cooled. The function is initiated by the input "water applied to boundaries" that is the outcome of the function

“Fight Fire Manually” and the water applied via the drenching system. Thus, the function “Activate Drenching System” is identified.

Name of Function	Activate Drenching System
Description	
Aspect	Description of Aspect
Input	Fire Assessed
Output	Water Applied to Boundaries
Precondition	N/A
Resource	N/A
Control	Water Drained
Time	N/A

Table 28 Function - Activate Drenching System

The Outcome of the function “Activate Drenching System” is to apply water to the boundaries. It is also used to apply water directly to the fire but the system is not designed for this and ultimately failed, especially due to the time it was initiated. The input that initiates this function is to have the fire assessed from the “Confirm Fire” function. The drenching system is controlled in accordance to the accumulation of water. The drainage system is required to function properly in order to have the water used for fire fighting drained. Thus the function “Drain Water” is identified.

Name of Function	Drain Water
Description	The extinguishing agent must be drained due to flooding concerns
Aspect	Description of Aspect
Input	Water Applied to Fire
	Water Applied to Boundaries
Output	Water Drained
Precondition	N/A
Resource	N/A
Control	N/A

Time	N/A

Table 29 Function - Drain Water

The fire fighting system must be equipped with adequate drainage capacity in order to reduce the risk of flooding from the applied water. The function “Drain Water” is initiated when water is applied either to the fire or the boundaries. The Output of the function is to have the aforementioned excess water removed.

Name of Function	Supervise From Bridge
Description	To report ashore and request help via distress signal if needed
Aspect	Description of Aspect
Input	Smoke Detected Manually
Output	Lookout Sent
	Tug Boat Requested
	Distress Signal
Precondition	Fire Assessed
Resource	N/A
Control	Report to Bridge
Time	N/A

Table 30 Function - Supervise From Bridge

The Output of the function “Supervise From Bridge” is to send the lookout to confirm and assess the fire after the alarms signalling. Another Output is to request a Tug Boat from ashore if the vessel is incapable of manoeuvring to shore without assistance. Finally, it has the Outcome to send a distress signal. The function’s performance is controlled by the report that was sent to the bridge after the alarms were interpreted from the “Interpret Alarm” function. The precondition for better performance of this function is to have the fire assessed accurately in order to supervise. The function can be initiated without prior alarm if the fire is detected via the CCTV the vessel was equipped with. Thus, the function “Supervise via CCTV” is identified.

Name of Function	Supervise via CCTV
Description	For any compartment that was equipped with CCTV
Aspect	Description of Aspect
Input	N/A
Output	Smoke Detected Manually
Precondition	N/A
Resource	N/A
Control	N/A
Time	N/A

Table 31 Function - Supervise via CCTV

The Outcome of this function is to provide an early detection system with the potential to assess the fire at an initial point. This outcome is the Input of the function "Supervise from bridge" in order to confirm the fire.

Name of Function	Send Helicopter Aid
Description	
Aspect	Description of Aspect
Input	Helicopter Granted Liftoff
Output	Water Applied to Fire
Precondition	Experienced Firefighter Prepared
Resource	N/A
Control	N/A
Time	N/A

Table 32 Function - Send Helicopter Aid

The Outcome of the function "Send Helicopter Aid" is to deploy experienced fire fighters on board and assist the fire fighting procedure. In order for this function to be initiated the helicopter must be granted permission to intervene. Thus, the function "Report Fire Ashore" is necessary. The precondition for this function to deliver on time is to have the fire fighters prepared. That state is also achieved via reporting to the authorities ashore.

Name of Function	Report Fire Ashore
Description	
Aspect	Description of Aspect
Input	Fire Confirmed
Output	Experienced Firefighters Prepared
	Helicopter Granted Liftoff
	Tug Boat Sent
Precondition	N/A
Resource	N/A
Control	Distress Signal
Time	N/A

Table 33 Function - Report Fire Ashore

The function is initiated after the fire is confirmed onboard. The Output of the function "Report Fire Ashore" is to have the ashore authorities prepare the experienced fire fighters that are standing by, and grand the helicopter the permission to intervene. This permission is given by the vessel's master after a distress signal is sent ashore. Thus, the required control from output of the function "Supervise from Bridge" is needed. Also, another Output of this function is to send the Tug Boat if it is requested by the master.

Even is the fire was contained the crew must take actions to assemble the passengers and ensure their safety.

Name of Function	Assemble Passengers
Description	
Aspect	Description of Aspect
Input	General Alarm Sounded
Output	Passengers Assembled
Precondition	Cabins Evacuated
	Evacuate Team Mustered
Resource	N/A
Control	N/A

Time	N/A

Table 34 Function - Assemble Passengers

The function Assemble Passengers is identified. The Outcome of this function is to assemble all the passengers to ensure their safety. The function is initiated when the general alarm is activated. The preconditions are to have the cabins evacuated and the hotel staff (named evacuate team here) mustered. Thus, the functions "Activate General Emergency Alarm" and "Check Cabins for Passengers" are identified.

Name of Function	Activate General Emergency Alarm
Description	
Aspect	Description of Aspect
Input	N/A
Output	General Alarm Sounded
Precondition	Power Provided
Resource	N/A
Control	N/A
Time	Fire Confirmed

Table 35 Function - Activate General Emergency Alarm

The function "Activate General Emergency Alarm" refers to the activation of the alarm calling the passenger to muster in the assembly stations. The precondition for the function to be effective is to have power provided since power shortages will delay the alarm. The Output of the function is to have the general alarm activated. The time the general alarm is activated depends on the time the fire is confirmed.

Name of Function	Check Cabins for Passengers
Description	
Aspect	Description of Aspect
Input	N/A
Output	Cabins Evacuated
Precondition	Evacuate Team Mustered
Resource	N/A

Control	General Alarm Sounded
Time	N/A

Table 36 Function - Check Cabins for passengers

The Outcome of this function is to ensure the cabins are evacuated. This function is controlled by the activation of the general alarm that signals the evacuate team to check the cabins. This constitutes the control of the function. The precondition is to have the evacuate team mustered and ready.

Variability of the functions

The function “Supervise via CCTV” did not perform as intended. The purpose of the function was to observe the vehicle deck for signs of smoke and fire, with regard to this incident. The screen became hazy before any alarm sounded but that was no cause for concern. The fire could be confirmed earlier if the function performed as imagined but, possibly due to neglect due to the increased number of sensors on the bridge, the detection was omitted.

The function “Interpret Alarm” did not perform as intended. Among others, the purpose of this function is to report the alarm to the bridge. The third engineer on watch insisted that there was a problem in the electrical circuits that sounded the alarms and bypassed a great amount of alarms himself. This internal variability resulted in an initial confusion when the fire was on early stages.

The function “Confirm Fire” did not perform as intended. The lookout sent by the bridge confirmed the fire from other crew members who smelled smoke. Even though the fire was correctly confirmed the variability of the output “fire assessed” increased because the lookout stopped in the restaurant where the other crew members were. This is a case of upstream-downstream variability of the function since the input varied. Also, the internal variability of the function is due to the lack of fire fighting equipment (mask) for the lookout to assess the fire earlier. Hence, the fire had more time to develop during those critical initial stages.

The function “Provide Power” had its performance varied on later stages. At first, the function carried out as intended but fire damage lead to power shortages in critical machinery in later stages.

These power shortages failed to provide power to the bow thrusters that was necessary for them to deploy. Hence, the function “Activate Bow Thrusters” had variability due to upstream-downstream coupling with the function “Provide Power”. Also, the function had internal variability from the fact that a lot of machinery was damaged from the fire.

The function “Cut Air Supply” had variability due to upstream-downstream coupling since even though the ventilation was stopped automatically, the fire screen doors were not closed by the fire party and discovered too late, allowing the fire to further develop.

The “Activate Drenching System” function was initiated by the chief engineer after interpreting the alarms. The function varied its performance since the water drains were partially blocked demanding continuous breaks on the water drenching system for the water not to be accumulated.

“Drain water” had its performance varied due to internal factors. Fire damage resulted in partial blockage of the drains that reduced the system’s capacity to remove excess water. This varied output greatly affected the drenching system performance.

The function “Report Fire Ashore” also had great variability from the expected performance. This variability was due to upstream-downstream couplings on the control “distress signal”. The function had the experienced fire fighters prepared but the tug boat was given permission to tug the vessel later due to no distress signal was issued by the master. The helicopter was also not granted permission to begin operation for the same reason.

The distress signal was not issued by the function “Supervise from Bridge” as intended. There was miscommunication as to whether help from ashore was needed or not, but no distress signal was issued. The function was also subject to variability because of the insistence of the third engineer that there was no fire but false alarms due to electrical damage.

The function “Fight Fire Manually” had water applied to the fire as an output. This output’s variability was increased since the fire hoses were too hot to operate and the party retreated with limited effect on the fire. This function’s output “fire doors close” was also late but due to upstream-downstream coupling on its precondition “fire assessed” that was too late.

The function “Maintain List” had great variability due to upstream-downstream coupling with the function “Drain Water”. List was created due to the accumulate water from the drenching system. The damage to list was mitigated by opening and closing the drenching system in a fashion that allowed water to be removed before more water was applied to the fire. The varied output increased the variability in the function “Maintain Course”.

“Maintain course” Output was to deliver the vessel at port, where fire fighters would attack the fire much more efficiently that it was attacked at sea. The function failed to perform as intended because of the upstream-downstream variability from the varied outputs that were the function’s preconditions. The bow thrusters were not activated because of the power shortage discussed above. The list was also not maintained because of the faulty drenching system as also discussed earlier.

“Activate Bow Thrusters” had its performance varied since the technical system surrendered to fire damage and power outages. Even though efforts were made to be initiated manually the results were negative.

The goal of delivering the vessel at port was achieved via a tug boat. The function “Tug Vessel” performed as intended but was initiated late because of the aforementioned miscommunication. The control “Tug boat requested” was too late because the master of the vessel did not issue a distress signal. However, the function was successful.

The function “Send helicopter Aid” varied because of upstream-downstream variability. The helicopter had the experienced fire fighter prepared and was ready for lift-off but the master did not request the assistance at first, thinking of the fire more of a challenge that could be tackled without external help.

The emergency alarm was activated successfully but relatively late because the fire confirmation was late.

The function “Evacuate Ship” was carried out successfully because of the double input that allowed the vessel to be towed when the ship’s seagoing was damaged.

Function	Output	Variability of the Output
Supervise via CCTV	Smoke Detected Manually	Detection was omitted. The hazy image of the CCTV was not seen by the officer on watch earlier than the alarms sounded.

Interpret Alarm	Report To Bridge	The third engineer insisted that the alarms was due to minor electrical damage to the electrical circuit
Confirm Fire	Fire Assessed	The lookout that was sent by the officer on the bridge was unable to enter the vehicle deck because he was not equipped with breathing apparatus. He later geared up but the fire had spread.
	Fire Confirmed	Due to miscommunication the fire was confirmed late.
Provide Power	Power Provided	Electrical damages resulted in power shortages in certain machinery
Cut Air Supply	Fire Suffocated	The fire screen doors were not closed allowing air and smoke to travel to and from the fire respectively.
Activate Drenching System	Water Applied to Boundaries	The performance of the drenching system was hindered because of the late activation and the need to take breaks for water not to accumulate further.
Drain water	Water Drained	Water was not drained as intended since the water drains were partially blocked. This created the need for the drenching system to take breaks for water not to accumulate further.
Report Fire Ashore	Tug Boat Sent	The distress signal was not issued until the vessels manoeuvrability was completely lost.
	Helicopter Granted Lift-off	The helicopter was not requested by the master.
Supervise from Bridge	Distress Signal	The distress Signal was not issued by the master of the vessel. This resulted in confusion on

		whether the master needed assistance from ashore or not.
Fight Fire Manually	Water Applied to Fire	The fire party was challenged by a fully developed fire in a confined space. The hoses were too hot to touch and the crew was unable to use the equipment.
Tug Vessel	Vessel Arrived at Port	The function performed positively but was initiated late due to delayed request.
Send helicopter Aid	Water Applied to Fire	The helicopter intervention was not requested by the master
Activate Bow Thrusters	Bow Thrusters Activated	The bow thrusters had been damaged by the fire and even with manual attempts they could not be deployed
Maintain course	Vessel Arrived at Port	The vessel could not arrive to port with her own means. The rudder had been damaged and the bow thrusters were also damaged.
Maintain List	List Maintained	The list could not be maintained because excess water had accumulated by the drenching system because the drainage system was partially blocked. Even with attempts to allow the drainage system to remove excess water, the need to contain the fire had negative effect on the vessel's list.

Table 37 Variability of the Outputs

Graphical Representation

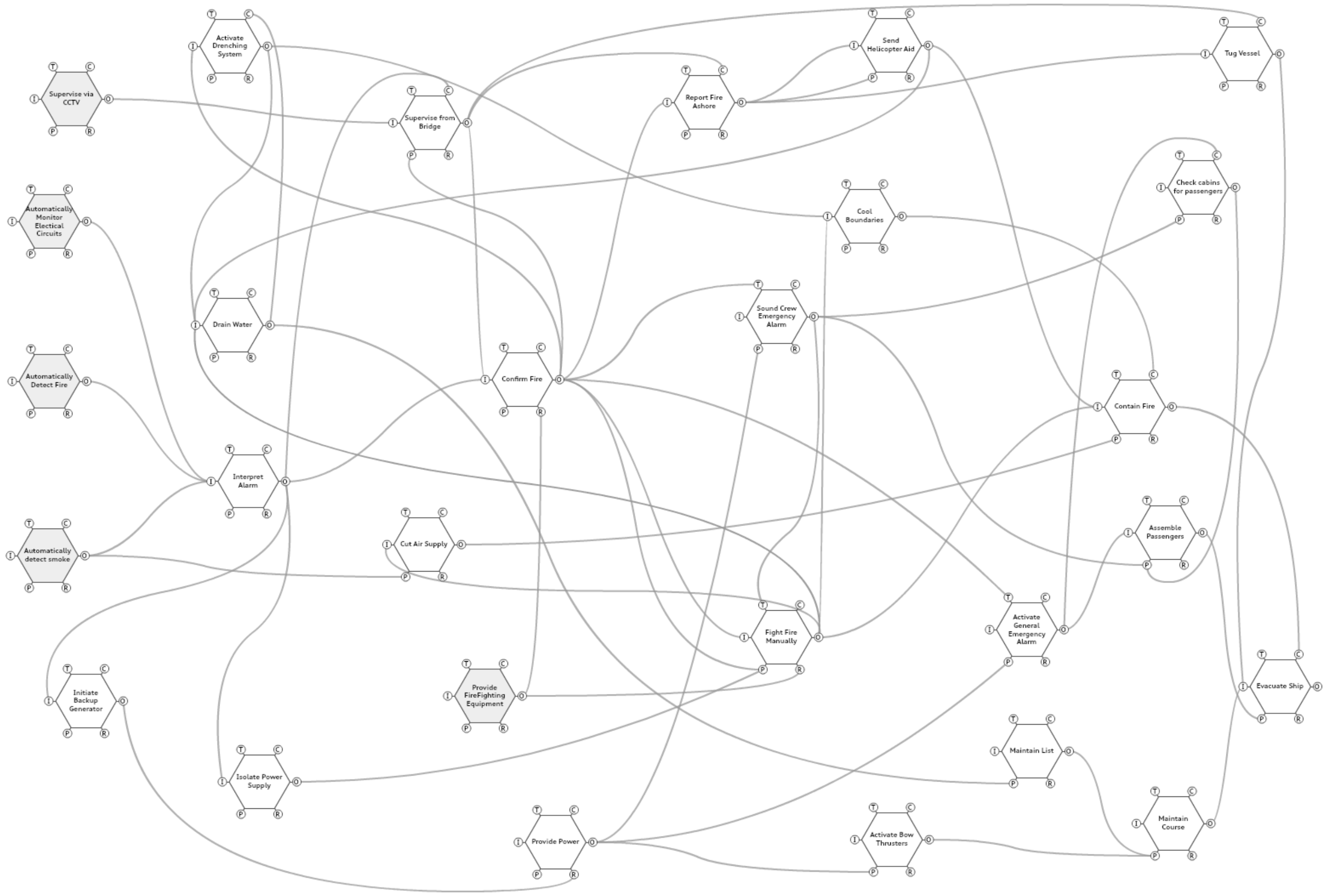

Figure 7 Graphical Representation 1

Functional Resonance

Rather than addressing safety issues like the initial investigation report, the FRAM attempts to suggest means of improvement regarding the resilience of the system. This thesis will attempt to make suggestions that would increase the responsiveness of the socio-technical system.

At first, the existing upstream-downstream couplings will be analysed to identify how the variability in a downstream function can increase the variability in downstream functions and may ultimately result in functional resonance.

The function “Evacuate Ship” had both Inputs’ variability increased as well as the control function’s. The vessel arrived at port that was necessary to initiate the function but both upstream functions that provided this Input had great variability. The function “Maintain Course” ceased to perform and the function “Tug Vessel” was initiated too late. The control function “Contain Fire” had increased variability that further delayed the function “Evacuate Ship”.

The function ultimately performed positively but the functional resonance that combined lead to the long delay until the function was performed.

The function “Tug Vessel” was delayed because the control ‘tug boat requested’ had increased variability. The upstream function “Supervise from Bridge” had upstream variability since the precondition ‘fire assessed’ was not precise. The ‘fire assessed’ state is the Outcome of the “Confirm Fire” function. The “Confirm Fire” function’s Input ‘lookout sent’ and Resource ‘fire fighting equipment provided’ variability resulted in the lookout not being able to fully assess the magnitude of the fire, thus varying the output ‘fire assessed’.

This hindered the master’s decision making discussed as a non-technical skill in the theoretical background. This variability in performance resulted in delayed request of the tug vessel. The false assessment led the master to believe that the vessel could reach port on her own means.

The function “Maintain Course” variability of outcome is due to the variability of upstream functions “Maintain List” and “Activate Bow Thrusters”. The bow thrusters could not be activated due to fire damage to the electrical circuit, hence the variability of the precondition ‘power provided’. The performance of the function “Maintain List” was also not as intended. The function had precondition to have the water drained to avoid free surface effect and uneven loading. The upstream function “Drain Water” had increased internal variability as discussed earlier and did not perform as it was imagined. This functional resonance resulted in variability on the downstream function “Maintain Course” making the function unable to perform at all.

The function’s “Drain Water” internal variability transferred to the downstream function “Activate Drenching System” hindering the latter function’s performance. The function “Activate Drenching System” also had the Input’s ‘fire assessed’ varied as discussed above. This functional resonance combined making the function unable to perform efficiently and even making it had negative outcomes on the aforementioned function “Maintain List”.

This variability was also transferred to the function “Cool Boundaries” that was not able to perform as intended. This resulted in variability of the control of the function “Contain Fire” that combined with the functional resonance from the variability of the functions “Maintain Course” and “Tug Vessel” resonate to vary “Evacuate Ship” performance.

The function “Contain Fire” also had high variability on other Inputs and Preconditions. The upstream function’s “Fight Fire Manually”, “Send Helicopter Aid” and “Cut Air Supply” were subject to variability of their Outcomes.

The function “Fight Fire Manually” had variability due to the upstream function’s “Sound Crew Emergency Alarm” delay. This delay was in turn due to the delayed fire confirmation that was discussed above. This resulted in delayed muster of the fire party even though the function itself performed as imagined. The inaccurate assessment of the fire and the delays resulted in the crew being unable to use the fire fighting equipment even though it was provided. This leads to the variability of the Outcome ‘close fire screen doors’ that was the input of the function “Cut Air Supply”. This variability transferred to the now downstream function “Contain Fire” that has the precondition of air deprivation.

Suggestions for Improvement

As presented in detail in chapter 3, the system should be managed to reduce the future occurrences of similar incidents. The system should also be managed for increased responsiveness when such occurrences happen. This can be done by: eliminating the hazards, prevention (referring to the addition of dampening barriers), facilitation (meaning the strengthening of existing barriers) and protection (reactive damage mitigation).

Suggestion 1.

The function “Drain Water” has internal variability as discussed earlier. This variability derives from the fact that the drains were partially blocked reducing the available flow of excess water. The high density of the vehicles in the vehicle deck reduced the manoeuvrability of the fire party. As a result the function “Fight Fire Manually” could also not perform as intended. Since the density of the vehicles result in variability in those functions this hazard’s elimination could reduce the functional resonance in downstream functions resulting in increased performance in function “Contain Fire”. The drop in variability of the function “Fight Fire Manually” may potentially influence variable Outcomes such as the variability in ‘close screen doors’. The actual and perceived challenge will be easier reducing the stress response of the team.

Eliminate the hazard created by the high density of the vehicles. Leave 'paths' for easy access by the fire fighting response team.

Suggestion 2.

As seen in the paragraph that described the functional resonance, the upstream functions "Confirm Fire" and "Activate Drenching System" are subject to upstream-downstream variability. The common variables are the Outputs of the function "Confirm Fire", 'fire confirmed' and 'fire assessed'. The addition of another function of a fire patrol operating such hazardous areas is a viable tool, given the number of crew members the vessel accommodates, that could increase the responsiveness of the system. This preventive measure provides an additional Input for the function "Confirm Fire" and for the function "Activate Drenching System" since a fire patrol is much more likely to detect the fire even by smell at early stages, where the drenching system would be more effective and the undeveloped clogging of the drains would not reduce the "Drain Water" performance. The complete effects are easily derived from the upstream-downstream analysis on functional resonance paragraph above. This could increase the resilience of the system given that such technical malfunctions happen.

Adding an additional fire patrol as a preventive measure for controlling fire spread at early stages.

Name of Function	Patrol Vehicle Deck
Description	
Aspect	Description of Aspect
Input	N/A
Output	Fire Observed
	Automatic Fire Fighting Initiated
Precondition	N/A
Resource	N/A
Control	N/A
Time	N/A

Table 38 Function - Patrol Vehicle Deck

This addition also changes the following function to comply with the model.

Name of Function	Activate Drenching System
Description	
Aspect	Description of Aspect
Input	Fire Assessed
	Automatic Fire Fighting Initiated
Output	Water Applied to Boundaries
Precondition	N/A
Resource	N/A
Control	Water Drained
Time	N/A

Table 39 Function - Activate Drenching Systems

The figure bellow illustrates the socio-technical system in the FRAM software with the addition of the new function.

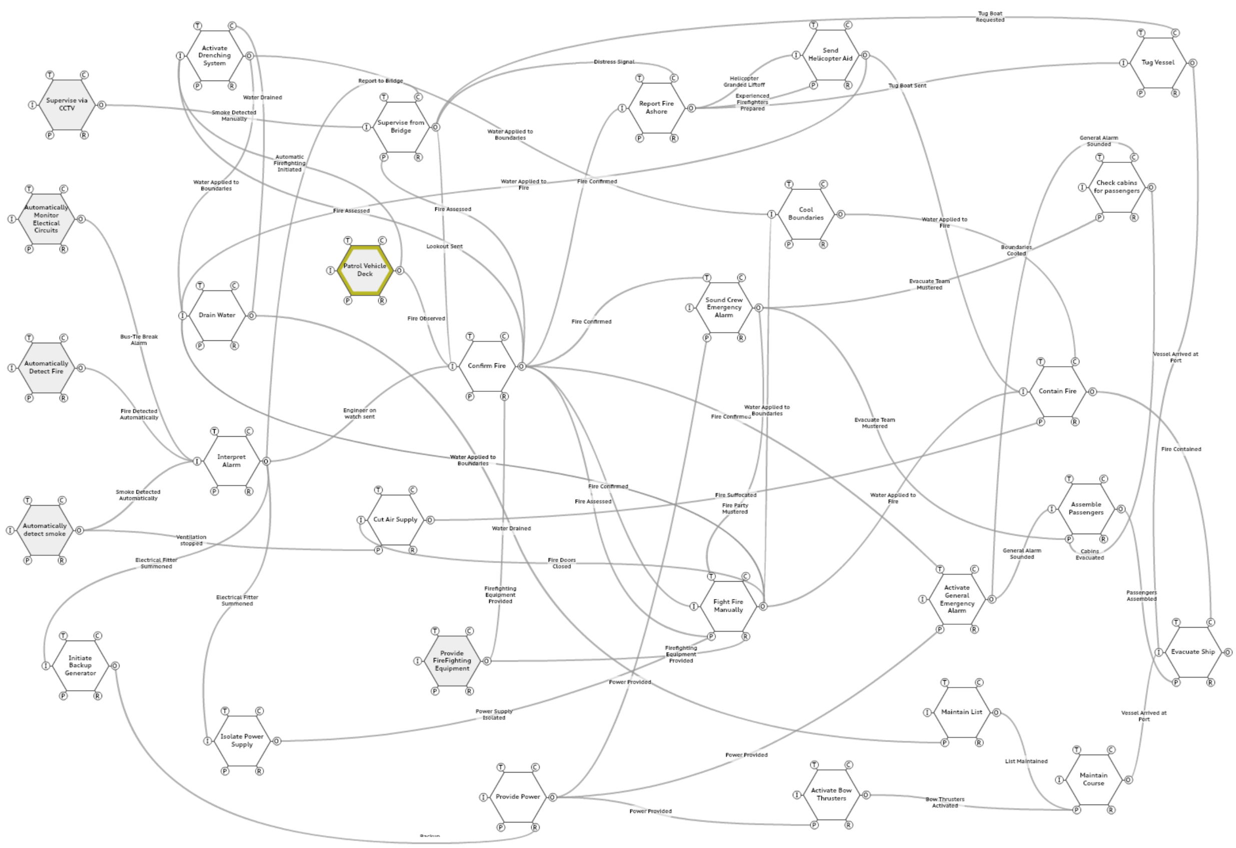

Table 40 Graphical representation 2

Suggestion 3.

Through the analysis the decision making abilities of the crew are seen as inadequate. Events such as misinterpreted alarms, neglected alarms that were bypassed and the refuse to assistance from ashore, provided by the port's authorities, accumulated to significant delays for assisting procedures. While single function's delays may not be significant the common factor of delayed decision making is responsible for a number of delays. These functions' variability resonates to significant delays on downstream functions.

Courses on non-technical skills for crew members as a measure to increase responsiveness through better decision making and better situational awareness.

Suggestion 4.

The added stress in emergency situations may lead to negative results and decreased performance. The function "Fight Fire Manually" should produce the Outcome 'close fire screen doors'. However, the demanding task of attacking a fully developed fire induced higher levels of stress probably making the team leader neglect this. While the fire party was unable to extinguish the fire, the main focus should be on containing the fire until the vessel is at berth. This, as shown before, requires the fire to be deprived of air to mitigate the spread. An additional Input to the function "Cut Air Supply" should be added to the system. Since fire in the kind of vessel we examine are difficult to extinguish and should be mitigated in best efforts, the confirmation of the fire should be an input to close the fire screen doors wherever possible.

Name of Function	Cut Air Supply
Description	
Aspect	Description of Aspect
Input	Fire Doors Closed
	Fire Assessed
Output	Fire Suffocated
Precondition	Ventilation Stopped
Resource	N/A
Control	N/A
Time	N/A

Table 41 Function - Cut Air Supply

This addition allows the initiation of the function when the fire is assessed to ensure proper procedure.

The figure bellow illustrates the socio-technical system in the FRAM software with the addition of the new function.

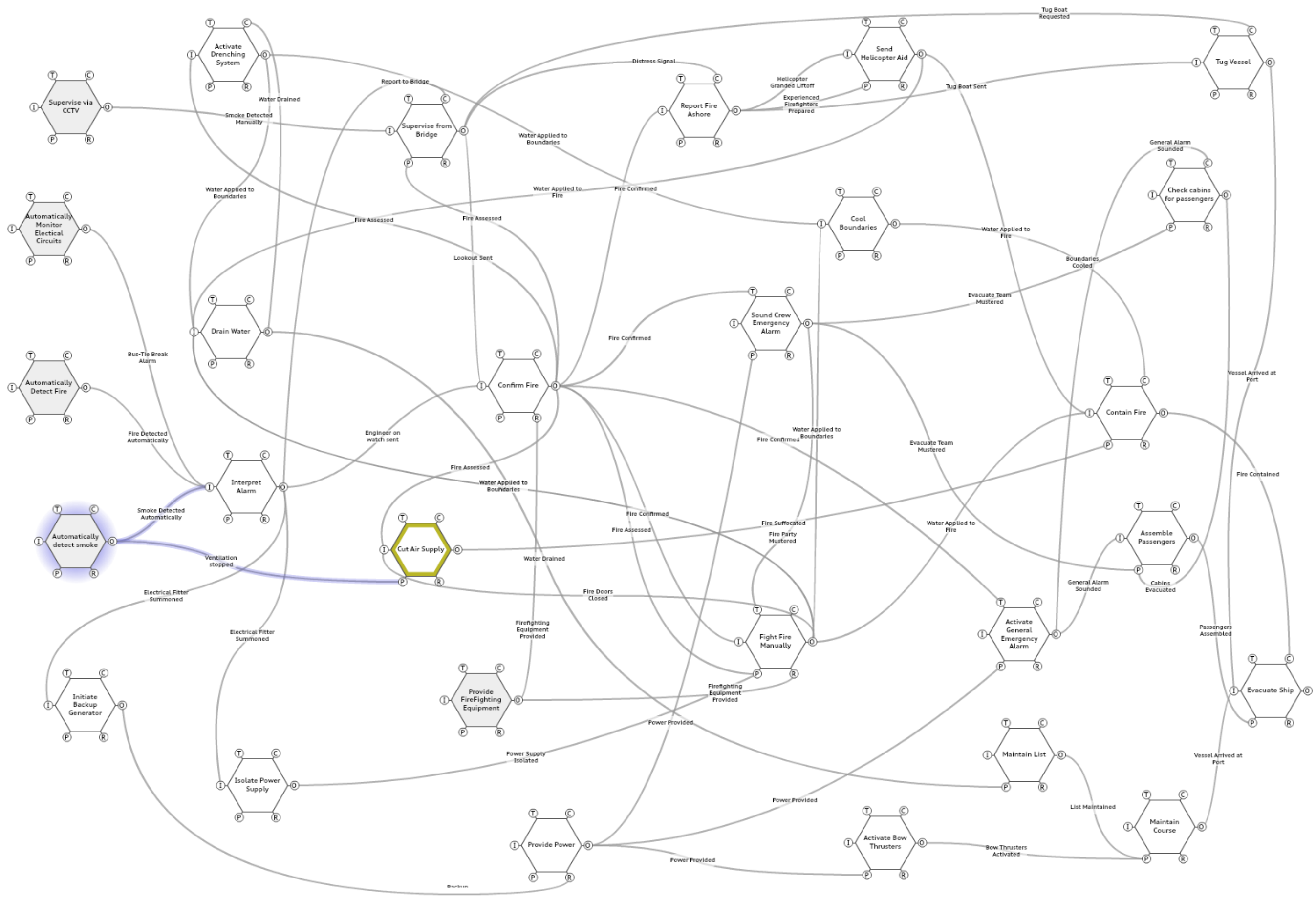

Figure 8 Graphical Representation 3

The socio-technical system with all the suggestions integrated is described by the following figure.

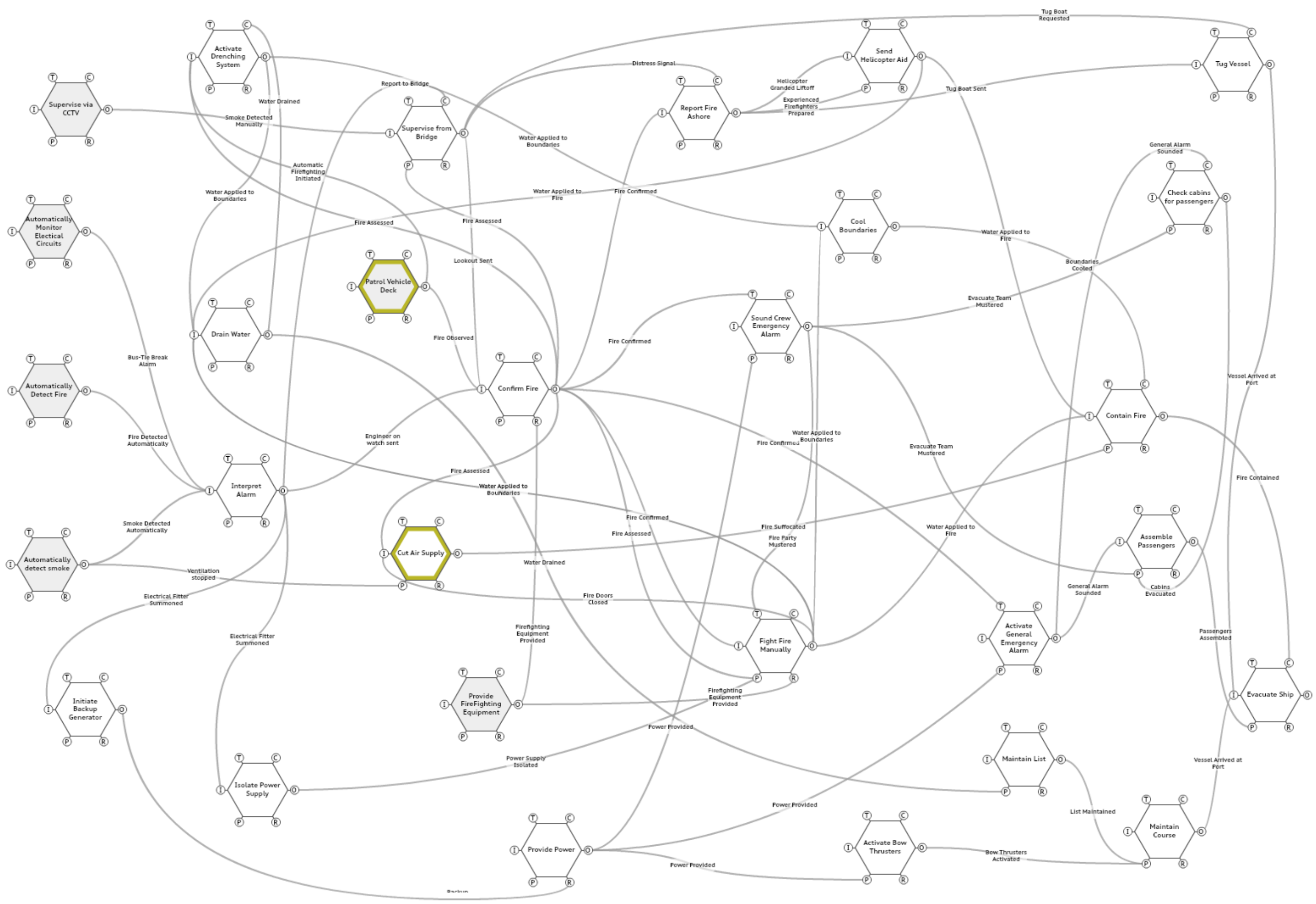

Figure 9 Graphical Representation 4

5.2. Case "*Edinburgh Castle*" 1998

Description of the Event

Edinburgh Castle (32353gt) was built in Italy and was UK registered Class 1 passenger ship. The boundaries of the main galley, bulkheads, deck, deckhead and doors were A60 class and in accordance with the International Convention for the Safety of Life at Sea (SOLAS 74).

On 21 August 1998, while the crew prepared breakfast for the passengers, fire was reported to bridge from the fire patrol operating the galley. The fire patrol contacted the bridge by radio, after an initial attempt to sound the alarm by breaking the glass panel that failed. The alarm in the galley was isolated and was covered by additional fire patrols in the area. This was common practice and the crew was well informed of the ways of communication in this situation. The report states that this made no difference in the latency. After the bridge watchkeeper was informed, a Public Address called the assessment party to the galley. The assessment party confirmed the fire in the area of three deep fat fryers and bridge was informed. Initial efforts with multiple portable CO_2 extinguishers failed. Also, fire blankets and chopping boards were used directly in the source of the fire. The interruption of power was prevented because the power contactor of one deep fat fryer had been welded close. Immediately after, the sprinkler system was initiated. Smoke detectors sounded in the surrounding compartments and the ventilation was stopped, with dampers closed. The bridge watchkeeper then reported the situation ashore to the DPA. The crew alert signal sounded and instructions for the passengers to not take any action were given. The firefighting continued with SCBA sets, one of which was reported and later found defective. This party was successful, and the sprinklers were shut down shortly after. Minutes later, the fire was reported extinguished. Fire was then reported on the ventilation ducting and steam was released combined with portable CO_2 extinguishers and boundary cooling to finally extinguish the fire. Hose parties and able seamen stood by for about four hours from the final report. The ventilation, alarm and sprinklers system's operation were restored four, nine and ten hours respectively after the final report.

The delayed report of the fire as well as the weaknesses in the control of fire parties, particularly when using self-contained breathing apparatus (SCBAs) were highlighted in the MAIB investigation. The investigation also reported that there was lack of accurate data on the vessel's ventilation system and damper arrangements. It was recommended that more comprehensive information on this and other aspects of the vessel's systems are made available to ship's staff before she is considered to comply with the requirement of ISM code.

Identification of the functions

With the benefit of hindsight provided by the investigation report the following functions were identified. It must be again noted that the function identification process is not linear but, in this thesis, best efforts are presented in the most understandable mean possible.

The identification of the functions focusses on the firefighting procedure, from the moment the fire is detected to the time it is extinguished. The system responsiveness is analysed thoroughly.

The function "Extinguish Fire" is identified. The purpose of this function is to extinguish the fire and thus, this is considered the Output of the function. The function is initiated when extinguishing agent is applied, either manually or automatically directly to the fire. In this instantiation the sprinklers were activated as they were supposed and the function “Fight Fire with Sprinklers” is identified. Also, the trained crew members that consisted the fire party manually attacked the fire. The function “Fight Fire Manually” is identified. As discussed earlier in the theoretical background, for the fire to be extinguished and prevented from spreading, the boundaries must be cooled. Thus, the function “Cool Boundaries” is identified. For this function to be successfully performed, and not be described as a function that contains fire rather than extinguishing, the success must be confirmed. This confirmation describes the control ‘fire confirmed extinguished’ and is provided by the function “Confirm Extinguish”. The function “Confirm Extinguish” is therefore also identified.

Name of Function	Extinguish Fire
Description	
Aspect	Description of Aspect
Input	Extinguishing agent applied
Output	Fire extinguished
Precondition	Boundaries cooled
Resource	N/A
Control	Fire spreads controlled
Time	N/A

Table 42 Function - Extinguish Fire

The function “Cool Boundaries” has Output ‘boundaries cooled’, the necessary precondition for the function “Extinguish Fire”. For the function to be initiated, the Input ‘water applied to boundaries’ is necessary. However, since the fire in this instantiation migrated through the ductings becoming unreachable the boundary cooling efforts were not optimal. The fire should be suppressed with steam in the ductings that can possibly prevent further spreads and assist boundary cooling. The functions “Fight Fire with Sprinklers” and “Fight Fire Manually” are the upstream functions that provide the needed Input. Also, the function “Release Steam in Ventilation” is identified. Finally, for the function “Cool Boundaries” to perform as intended, the crew must have nearby passengers evacuated from nearby compartments to prevent any harm done. The function “Evacuate Restaurant Area” is identified.

Name of Function	Cool Boundaries
Description	
Aspect	Description of Aspect
Input	Water applied to boundaries
Output	Boundaries cooled
Precondition	Suppress mitigation with steam
	Nearby passengers removed
Resource	N/A
Control	N/A
Time	N/A

Table 43 Function - Cool Boundaries

The Output of the function "Release Steam in Ventilation" is to suppress fire spread using steam in the ventilation ductings. It's a technological function that is initiated when smoke is detected in the ventilation. The function "Release Steam in Ventilation" is controlled by a supervisor who decides on the proper use of the system. Thus, the function "Supervise" is identified. Also, the smoke is detected via smoke detectors in accordance with the systems capabilities to monitor the fire. The function "Monitor Fire" is identified.

Name of Function	Release Steam in Ventilation
Description	Ineffective. Stopped too late, when there was fog
Aspect	Description of Aspect
Input	Smoke detected in ventilation
Output	Suppress spread with steam
Precondition	N/A
Resource	N/A
Control	Steam release initiated
Time	N/A

Table 44 Function - Release Steam in Ventilation

The function supervise combines the assessment data and take actions that initiate downstream functions. Some of the downstream functions feed data back to the "Supervise" function. The function is initiated when the fire is reported via radio. Thus, the function "Detect Fire Initiation Manually" is identified. The function can also be initiated by the "Detect Fire Initiation Automatically" but since it was common practice for the crew to shut the alarm down and operate with fire patrols in the area (a practice considered to be as effective as the automatic detection system) it is only referred for a more complete investigation and could be omitted. The Outputs of the function "Supervise" are to initiate steam release into ductings if that is necessary, to remotely close the ventilation dampers and to make Public Announcement to muster the crew and alert of the incident. In order to perform as intended, data is needed as a Resource for decision making. The fire assessment data derive from the "Monitor Fire" function that was identified earlier and will be discussed later on.

Name of Function	Supervise
Description	
Aspect	Description of Aspect
Input	Radio report
Output	Steam release initiated
	Ventilation dampers closed
	Public address initiated
	alarm activated
Precondition	N/A
Resource	Fire assessed
Control	N/A
Time	N/A

Table 45 Function - Supervise

The Outcome of the function "Detect Fire Initiation Automatically" is to activate the alarm and notify the crew member on watch of the potential fire. This system was shut down during operation in the galley and replaced by fire patrols. The official investigation stated that this change should make no difference in the detection time and ultimately in the response time.

Name of Function	Detect Fire Initiation Automatically
Description	Alarm was shut down
Aspect	Description of Aspect
Input	N/A
Output	Alarm activated
Precondition	N/A
Resource	N/A
Control	N/A
Time	N/A

Table 46 Function - Detect Fire Initiation Automatically

The Outputs of the function "Detect Fire Initiation Manually" are to report the fire initiation to the bridge via the portable radio the crew members on watch were equipped with during patrolling, to activate the alarm and to observe the fire in order to monitor. Thus, it constitutes the upstream function of the function "Monitor Fire" which is initiated when the fire is first observed.

Name of Function	Detect Fire Initiation Manually
Description	Additional fire patrols to cover for disabled alarm
Aspect	Description of Aspect
Input	N/A
Output	Radio report
	Alarm activated
	Fire observed
Precondition	N/A
Resource	N/A
Control	N/A
Time	N/A

Table 47 Function - Detect Fire Initiation Manually

To fight fire manually, two separate functions have been identified. When the fire is observed the fire patrol used portable CO2 extinguisher to fight the fire. After the fire-fighting team was mustered the fire was first attacked by the first aid team followed by the fire party that was better prepared. Thus, the function “Fight Fire Manually (First Aid)” and the function “Fight Fire Manually (Fire Party)” are identified to increase detail.

The function “Fight Fire Manually (Fire Party)” is already identified as a provider for the necessary input ‘extinguishing agent applied to fire’ that is the Input of the function “Extinguish Fire”. Obviously, one Output of this function is ‘extinguishing agent applied to fire’ but also, since the function was used for boundary cooling, the ‘water applied to boundaries’ Output is identified as was needed earlier. The fire party needed information about the development of the fire in order to handle the incident. This precondition ‘fire assessed’ is provided by the “Monitor Fire” function that is already identified. Moreover, the fire party required the proper extinguishing agent to be provided as a Resource. The function “Provide Extinguishing Agent” is identified.

Name of Function	Fight Fire Manually (Fire Party)
Description	
Aspect	Description of Aspect
Input	Proceed to fire party
Output	Extinguishing agent applied
	Water applied to boundaries
Precondition	Fire assessed
Resource	Extinguishing agent provided
Control	N/A
Time	N/A

Table 48 Function - Fight Fire Manually (Fire Party)

The purpose of the function “Fight Fire Manually (First Aid)” is to attack the fire to prevent further development until the fire party is prepared. When this function completes, the system proceeds to the “Fight Fire Manually (Fire Party)” function for more effective damage mitigation and better chances of extinguishing the fire. The observations of the first aid group constitute an additional assessment of the magnitude of the fire. Those observations are necessary for the fire party to proceed. The function is initiated as soon as the fire party is mustered. In this instantiation the fire party was mustered following a Public Address issued by the bridge. Thus, the function "Public Address to muster assessment party" is identified. Also, it is necessary for the function to perform as intended to have nearby passengers evacuated to prevent any harm done.

Name of Function	Fight Fire Manually (First Aid)
Description	
Aspect	Description of Aspect
Input	Fire party mustered
Output	Initial fire assessed
	Proceed to fire party
Precondition	Nearby passengers evacuated
Resource	Provide extinguishing agent
Control	N/A
Time	N/A

Table 49 Function - Fight Fire Manually (First Aid)

The function "Fight Fire with Sprinklers" was identified earlier in this thesis. The function is initiated when the sprinklers are activated. The Input of the function is 'sprinklers activated'. The necessary precondition for this function to perform is to have extinguishing agent provided. This Precondition is the Output of the "Provide Extinguishing Agent" function which is used as a general precondition where required. The sprinklers are not designed to extinguish the fire, especially when the fire is due to heated oil. Partly, it is used to apply water to the boundaries in an effort to cool them down.

Name of Function	Fight Fire with Sprinklers
Description	
Aspect	Description of Aspect
Input	Sprinklers activated
Output	Extinguishing agent applied
	Water applied to boundaries
Precondition	Extinguishing agent provided
Resource	N/A
Control	N/A

Time	N/A

Table 50 Function - Fight Fire with Sprinklers

The function “Public Address to muster assessment party” is identified earlier in this thesis. The public announcement system is initiated when the alarm is sounded by the supervisors. Thus, the Input is the state ‘alarm sounded’ and the Control is ‘Public address initiated’. The Control state is discussed earlier in the “Supervise” function which has this additional Output. In order for the fire party to have clear instructions on which muster station is the most efficient, as well as for information on the location of the fire the fire need to be assessed at least in a basic level. The Resource ‘fire assessed’ is provided by the “Monitor Fire” function that is already identified. The Output of the function is to have the first aid party mustered since the fire party initiated the efforts under first aid’s completion. Also, the Output ‘nearby passengers evacuated’ is provided by this function in addition to the “Evacuate Restaurant Area” function that is identified through the analysis in later steps. The function “Sound the Alarm” is identified as a necessary function to provide the Input.

Name of Function	Public Address to muster assessment party
Description	
Aspect	Description of Aspect
Input	Alarm Sounded
Output	Fire party mustered
	Nearby passengers evacuated
Precondition	N/A
Resource	Fire assessed
Control	Public address initiated
Time	N/A

Table 51 Function - Public Address to muster assessment party

The function “Monitor Fire” purpose is to assess the fire and provide the crew with data to efficiently handle the incident. The function also includes the smoke detection sub-function which is necessary to provide data to the supervisors and the fire attack party. Given that the smoke detector did not malfunction and does not appear to be part of the upstream-downstream couplings, it is decided that it will be included in the “Monitor Fire” function. Parts of the aforementioned data come from the assessment of the first aid party and are useful for the fire attack party when re-entering. Thus 'initial fire assessed' is identified as a Resource for this function.

Name of Function	Monitor Fire
Description	
Aspect	Description of Aspect
Input	Fire observed
Output	Fire assessed
	Smoke detected in ventilation
	Sprinklers activated
Precondition	N/A
Resource	Initial fire assessed
Control	N/A
Time	N/A

Table 52 Function - Monitor Fire

Since the automatic detection system was shut down, the alarm needed to be activated manually. In this instantiation the variability of the Output that will be discussed later, creates the need for a separate function "Sound the Alarm". The break-glass alarm was isolated as part of the modifications to the fire detection socio-technical system. The function is initiated by the activation of the alarm. This activation is inseparable from the fire detection since it is the first action that needs to take place. Thus, the function "Detect Fire Initiation Manually" is identified. The alarm in the proper functioning socio-technical system should be activated by the automatic fire detection system that was shut down in this instantiation. The function "Detect Fire Initiation Automatically" is again identified to distinguish this variability in the system during the incident. The function can also be initiated by the "Supervision" function that is identified.

Name of Function	Sound the Alarm
Description	The break glass alarm was isolated
Aspect	Description of Aspect
Input	Alarm activated
Output	Alarm sounded

Precondition	N/A
Resource	N/A
Control	N/A
Time	N/A

Table 53 Function - Sound the Alarm

The function "Provide Extinguishing Agent" was identified via previous functions as a general precondition for any function that required an extinguishing agent to be available. Inputs, Preconditions, Resources, Control and Time are not identified but it is considered necessary under general maintenance to have all the necessary equipment to assist the fire-fighting procedure.

Name of Function	Provide Extinguishing Agent and Fire-fighting Equipment
Description	
Aspect	Description of Aspect
Input	N/A
Output	Extinguishing agent provided
Precondition	N/A
Resource	N/A
Control	N/A
Time	N/A

Table 54 Function - Provide Extinguishing Agent and FireFighting Equipment

The function "Confirm Extinguish" is identified in the early stages of the identification process. The necessary Input for the function to initiate is to extinguish the fire. The fire is confirmed extinguished but as discovered later on, the fire had minor spreads. This first confirmation initiated the function "Confirm Extinguish" that was required to ultimately complete the "Extinguish Fire" function without any doubt. This function was carried out by the fire party standing by as is required to prevent further spreading. Since the initiation and completion of the function is controlled by the fire party, the necessary state 'situation controlled' is the Control of the now identified function "Fire Party Standby". To successfully confirm the extinguish fire spreads must be controlled. Thus, the necessary Precondition 'fire spreads controlled' is provided by the function "Prevent Fire Spread". The function "Prevent Fire Spreads" is identified.

Name of Function	Confirm Extinguish
Description	
Aspect	Description of Aspect
Input	Fire extinguished
Output	N/A
Precondition	Fire spreads controlled
Resource	N/A
Control	Situation monitored
Time	N/A

Table 55 Function - Confirm Extinguish

The function "Fire Party Standby" is identified and initiated by the Output of the "Extinguish Fire" function 'fire extinguished'. The purpose of the fire party standing by is to monitor the situation and intercept possible re-ignitions in an undeveloped stage. The two functions must coexist until the vessel arrives at port and experienced fire fighters take over. Moreover, the fire party must also have the necessary fire-fighting equipment that is provided by the "Provide Extinguishing Agent" function.

Name of Function	Fire Party Stand by
Description	
Aspect	Description of Aspect
Input	Fire extinguished
Output	Situation monitored
Precondition	Extinguishing Agent Provided
Resource	N/A
Control	N/A
Time	N/A

Table 56 Function - Fire Party Stand by

The function "Prevent Fire Spreads" is identified earlier in the identification process. The purpose of this function is to take the actions required to prevent the fire from further spreading.

This is described by the Output of the function “Prevent Fire Spreads” which is the state ‘fire spreads controlled’. For this function to perform as intended, the ventilation dampers must be closed to prevent the fire from spreading through the air ductings. This is recognized as a Precondition. The Precondition is provided by the function “Supervise” that evaluates the data from other functions to decide to close the ventilation dampers. To prevent fire from spreading through radiation, the boundaries must be cooled down. This additional Precondition is the state ‘boundaries cooled’ that is the Output of the “Cool Boundaries” function that was previously identified. The fire is also prevented from spreading with the assistance of the vessel’s built in steam system that allows steam to be released in the ductings to suppress fire spreading. The Resource ‘Suppress spread with steam’ is provided by the “Release Steam in Ventilation’ function’s Output and primary purpose. The function “Release Steam in Ventilation” is identified previously. The “Prevent Fire Spreads” function’s Output is the state of control regarding fire spreading. The Output ‘fire spreads controlled’ is necessary to extinguish the fire and therefore are used as Control in the “Extinguish Fire” function.

Name of Function	Prevent Fire Spreads
Description	
Aspect	Description of Aspect
Input	N/A
Output	Fire spreads controlled
Precondition	Ventilation dampers closed
	Boundaries cooled
Resource	Suppress spread with steam
Control	N/A
Time	N/A

Table 57 Function - Prevent Fire Spread

The function “Evacuate Restaurant Area” is identified. The Output of this function is the state ‘nearby passengers evacuated’. This function continues to perform until the incident is resolved and the way the function performs is controlled by the state ‘fire spreads controlled’ since it is a necessary requirement for proper evacuation of the areas that are under threat. The function is initiated by the fire being observed to calmly evacuate the restaurant and surrounding areas. Thus, the function "Detect Fire Initiation Manually" is required for its necessary Output 'fire observed'.

Name of Function	Evacuate Restaurant Area
Description	
Aspect	Description of Aspect
Input	Fire observed
Output	Nearby passengers evacuated
Precondition	N/A
Resource	N/A
Control	Fire spreads controlled
Time	N/A

Table 58 Function - Evacuate Restaurant Area

Variability of the functions

The function "Detect Fire Initiation Manually" had several Outputs. While the fire was detected during the early stages by the fire patrol, thus initiating the function "Monitor Fire" as it was imagined to do, the Output 'alarm activated' was initiated later than expected. This is due to the isolation of the glass-break alarm as part of the automatic fire detection system that was deactivated. The variability on the Output 'alarm activated' caused the downstream function "Sound the Alarm" to be performed later than it was supposed to. The fire patrol reported the incident via radio and the bridge was ultimately notified.

The function "Detect Fire Initiation Automatically" had increased variability of the Output 'alarm activated'. The reason for this is the alarm shut-down that was common practice. Even though it was common practice it is considered that the socio-technical system involved in the fire-fighting efforts was designed to perform with this tool enabled and since it was shut down, the function did not perform at all.

The function "Supervision" was subject to internal variability. While the alarm was activated and the master initiated the function "Public Address to Muster Assessment Party" as intended, the Output 'ventilation dampers closed' was performed too late. This resulted in upstream-downstream variability that will be discussed in detail in later paragraphs. Additionally, the initiation of the smothering steam system in the ventilation was later than required and that resulted in variability of the Output "steam released initiated". This delay may have caused the steam smothering system's performance to be sub-optimal.

The function "Prevent Fire Spreads" did not perform as intended. The necessary preconditions were to have the boundaries cooled (that did not result in upstream-downstream variability since the function "Cool Boundaries" did perform as intended) and to close the ventilation dampers. Since the ventilation dampers were not closed on time, the fire spread in the ductings resulting in the function "Prevent Fire Spreads" to not perform precisely. The Resource 'supress spread with steam' was also subject to variability since the smothering system did not have the desired performance as discussed earlier.

The function "Evacuate Restaurant Area" was subject to internal variability of the Output. The Output 'nearby passengers evacuated' had increased variability since the passengers had not be removed by the restaurant staff even though the fire was detected. The needed evacuation was provided by the public announcement issued by the bridge but this path created undesired stress among the passengers. This variability may not be adequate to produce downstream variability in this instantiation but the system's resilience, meaning the ability to cope with this loss of performance in this function, should not be taken for granted.

The technological function "Fight Fire with Sprinklers" was subject to variability of one of the Outcomes. While the sprinklers were activated as intended and used to apply water to the boundaries of the restaurant, the application of water directly to the fire resulted in increased amounts of steam released, making fire-fighting efforts significantly harder. This possibly increased the task the fire-fighting parties encountered increasing their stress levels and reducing their performance. In a sense, the function initiated too late, when the temperatures of the room were higher and water vapour was immediately produced as water droplets came in contact with hot surfaces.

The function "Sound the Alarm" experienced upstream-downstream variability due to variability of the Input 'alarm activated'. While the alarm was finally activated, the isolation of the glass-break alarm was responsible for a minor latency in the initiation of the function.

The function "Release Steam in Ventilation" did not perform as imagined. The function's purpose is to have steam released in the ventilation ductings to prevent the fire from traveling through the air vents and to smother the fire. The smothering system did not manage to prevent the fire from spreading. Also, due to fire on the ventilation itself, the released steam reduced the crew's visibility making fire-fighting efforts less effective.

The function "Prevent Fire Spreads" had its performance hindered. The precondition 'ventilation dampers closed' was delivered too late and the fire had sufficient time to spread to the ventilation system. The dampers were not left open for enough time for the fire to spread beyond this compartment but that is a serious hazard that was avoided in this instantiation. Additionally, the steam smothering system that was required to provide the needed Resource had not been as efficient as presumed.

The function "Confirm Extinguish" was subject to upstream-downstream variability of the Precondition 'fire spreads controlled'. This Precondition is the Output of the "Prevent Fire Spreads" function that was subject to variability as described earlier. This caused the confirmation to be too late since continued spreads kept on emerging in this instantiation. While the Input 'fire extinguished' could not be granted, this did not prevent the function from performing as intended. This upstream-downstream coupling will be discussed in detail in the functional resonance segment later. It is important to note that this active feedback between the two functions ensured the ultimate completion of both.

The function "Provide Extinguishing Agent and Fire-fighting Equipment" did not perform entirely accurately. This internal variability of the Output was because one of the SCBA sets malfunctioned but since the fire was developed and impossible to be contained at the moment the malfunction occurred, its effects were limited. However, this malfunction may have been of importance if it occurred in a different moment.

The function "Extinguish Fire" did not perform as imagined. The variability of the Input 'extinguishing agent applied' that derived from the function "Fight Fire with Sprinklers" was an ineffective Input for the function "Extinguish Fire". This was covered by the alternative Input of the function that was produced by the function "Fight Fire Manually (Fire Party)". The latter function was successful at producing the Outcome but not as effective at the early stages, adding latency to the function "Extinguish Fire".

Function	Output	Variability of the Output
Detect Fire Initiation Manually	alarm activated	The break-glass alarm was isolated and could not be used. The attempt to initiate the alarm from the break-glass alarm combined with the need for an alternative solution to activate the alarm resulted in the alarm being activated later than was expected in this instantiation.
Detect Fire Initiation Automatically	alarm activated	The automatic fire detection system was deactivated as was common practice. The lack of this barrier is likely to increase the latency the alarm is being activated. Technological systems are more reliable than the human element which can be more easily distracted. In this instantiation this function did not perform at all.
Supervision	ventilation dampers closed	The ventilation dampers should be closed as soon as the fire was detected to prevent spreading through the ductings and to assist the extinguishing process by depriving the fire from air.
	Steam released initiated	The smothering steam was released too late because it was not prioritized and therefore was ineffective against a developed fire of this kind. The fire had spread to the ductings and the steam was not as effective as imagined.
Prevent Fire Spreads	Fire spreads controlled	Since the necessary requirement were not met in this instantiation, the fire spread in the ductings. It is important to note that the location of the fire made it easier to spread in hard to reach areas.
Fight Fire with	Extinguishing agent	The extinguishing agent that was applied to fire

Sprinklers	applied	was ineffective primarily because of the time it was initiated. The Sprinklers are ineffective in a fully developed fire regarding the process of extinguishing.
Sound the Alarm	Alarm sounded	The initiation of the function was later than expected since the fire detection system was inactive. The variability of this Output is considered minor but may be important through functional resonance analysis.
Release Steam in Ventilation	Suppress spread with steam	The function was initiated late and the fire had already spread in the ductings in this instantiation. This made the smothering system less effective against a fire that had spread in the ductings.
Extinguish Fire	Fire extinguished	This function did not perform as expected since fire spreads continued long after the fire had been extinguished in the area of the three deep fat fryers. This minor variability of the Output increased the risk and the duration of the incident significantly.
Confirm Extinguish	Fire confirmed extinguished	The fire could not be confirmed extinguished because of continuing ignitions in the ductings. Until the fire was extinguished from every possible location, the confirmation could not be completed.
Provide Extinguishing Agent and Fire-fighting Equipment	Extinguishing agent and extinguishing equipment provided	One of the SCBA masks failed to provide breathing air to a crew member during re-entry. The crew member had to retreat in risk of suffocation

Table 59 Variability of the Outputs 2

Graphical Representation

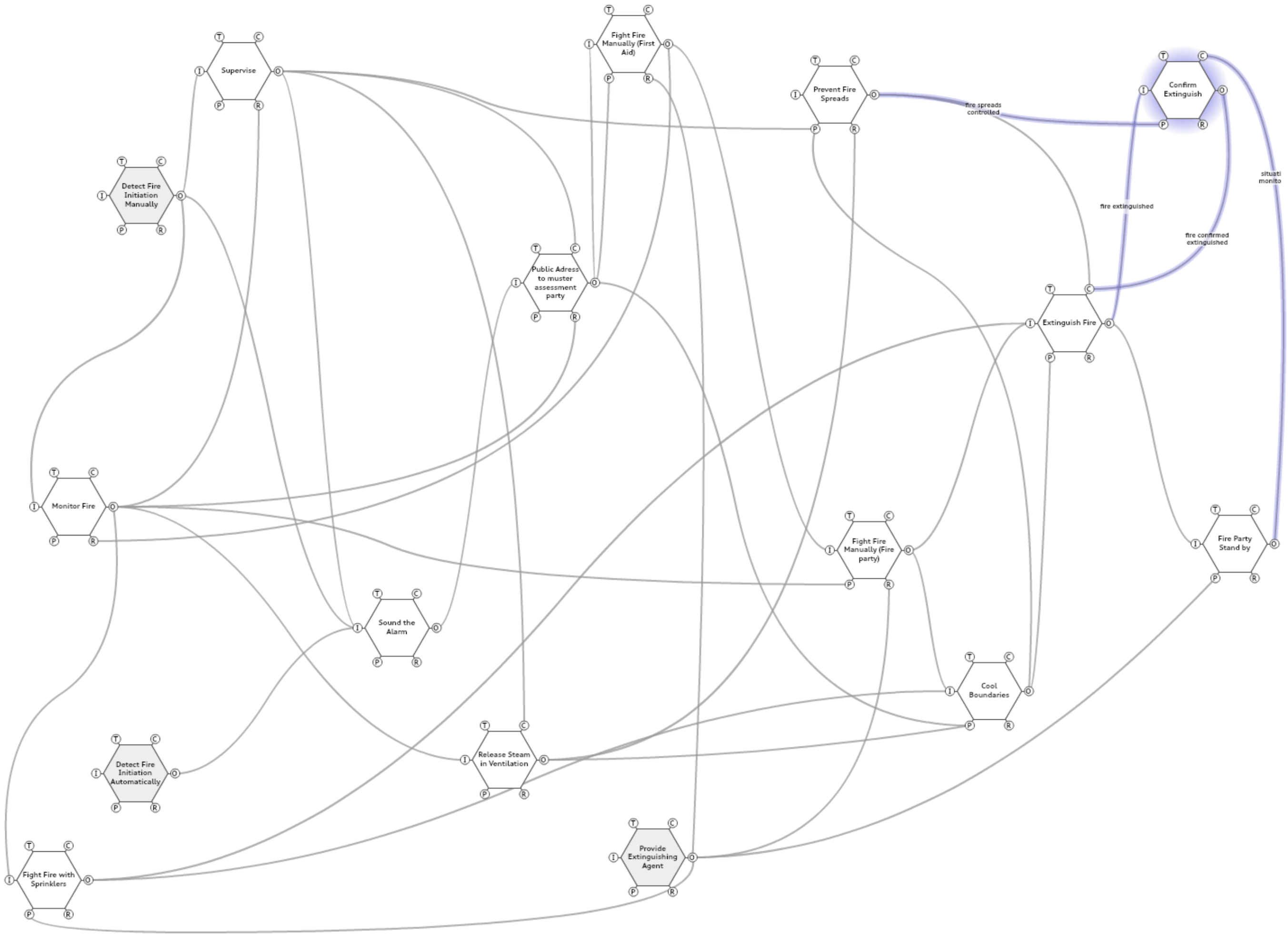

Figure 10 Graphical Representation 5

Functional Resonance

Rather than addressing safety issues like the initial investigation report, the FRAM attempts to suggest means of improvement regarding the resilience of the system. This thesis will attempt to make suggestions that would increase the responsiveness of the socio-technical system.

At first, the existing upstream-downstream couplings will be analysed to identify how the variability in a downstream function can increase the variability in downstream functions and may ultimately result in functional resonance.

The function's "Detect Fire Initiation Manually" performance varied the output 'alarm activated' causing the function "Sound the Alarm" to be initiated later than expected. This upstream-downstream variability of the Output combined with the variability of the Output 'public address initiated' that was performed late by the "Supervision" function resonated to increased latency of the function "Public Address to muster Assessment Party". Even though the variability on the Output of the two functions that provided the Input and the Control for the function "Public Address to Muster the Assessment Party" was minor and the respected latency was low, the functional resonance analysis explains the delayed initiation of the latter function. Of course this is not to suggest that the function failed or the response was insufficient but only to point out the reasons it was not optimal.

The upstream-downstream variability of the Output 'extinguishing agent applied to fire' resulted in variability of the Input of the function "Extinguish Fire" as a result of the sprinklers not outputting the imagined performance. Moreover, the variability of the Output of the function "Supervise" caused via upstream-downstream variability of the Precondition 'ventilation dampers closed' resulted in the function "Prevent Fire Spreads" to not function efficiently. This caused the socio-technical system to be ineffective in preventive the fire spreads, which was also a Control for the function "Extinguish Fire". Also, the malfunction of the SCBA set that caused a crew member to retreat increased the upstream-downstream variability of the function "Fight Fire Manually (Fire Party)" that increased the variability of the Output 'extinguishing agent applied'. This functional resonance of the aforementioned three functions significantly increased the variability of the function "Extinguish Fire" causing greater variability of the Outcome 'fire extinguished'. This illustrates how minor sources of variability of lesser magnitude can resonate to increase the variability significantly on downstream functions.

The function "Cool Boundaries" in this instantiation had increased variability of the Input 'water applied to boundaries' by the inefficiency of the sprinklers system described in the "Fight Fire with Sprinklers" function. It is important to note that the function "Cool Boundaries" appears to have dampening effects on the disturbances having the advantage of two separate Inputs from two separate functions. The variability from functional resonance in this situation was mitigated by this effect.

It is important to note that even the function “Prevent Fire Spreads” was subject to variability through functional resonance. The variability of the Output ‘ventilation dampers closed’ of the function “Supervise” resonated with the internal variability of the Output ‘suppress spread with steam’ of the function “Release Steam in Ventilation”. This functional resonance increased the variability of the Output of the function “Prevent Fire Spreads” that resonated with the variability of the functions “Supervise” and “Fight Fire Manually (Fire Party)” to significantly increase the variability of the function “Extinguish Fire” that was described earlier.

One of the functions that resonated and increased the variability of the function “Extinguish Fire” is the variability of the Output ‘extinguishing agent applied to fire’ provided by the function “Fight Fire Manually”. This function was also subject to variability through functional resonance since both the Input was delivered later than optimal the Resource included the SCBA set malfunction that has been described. This functional resonance combined and increased the variability of the function’s “Fight Fire Manually” Outcome. This variability of the Output resonates with the variability from the aforementioned functions.

The last identified coupling in this instantiation is the functional resonance that resulted by the variability of the Outputs of the “Extinguish Fire” and “Prevent Fire Spreads” functions. This functional resonance resulted in imprecise performance of the “Confirm Extinguish” function. The fire was not under control because of the continued re-ignitions. This resulted in increased time to complete the function “Confirm Extinguish” since the alternating variability of the Input and Precondition of the function (‘fire extinguished’ and ‘fire spreads controlled’ respectively) significantly increased the variability of this function.

Suggestions for Improvement

As presented in detail in chapter 3, the system should be managed to reduce the future occurrences of similar incidents. The system should also be managed for increased responsiveness when such occurrences happen. This can be done by: eliminating the hazards, prevention (referring to the addition of dampening barriers), facilitation (meaning the strengthening of existing barriers) and protection (reactive damage mitigation).

Suggestion 1.

A hazard that emerged through the investigation of this incident was the distressed evacuation of nearby passengers. This was caused because the passengers were alerted via the

Public Announcement. It must be taken into account that the passengers do not have the same capabilities as trained crew members do, including, but not limited, to situational awareness and the detailed understanding of the vessel's structure. Nearby passengers could be alerted as soon as the fire was observed to ensure reduced stress levels that may result in evacuating in a calm manner. The public announcement is not a bad practice but, given the opportunity, the socio-technical system can respond more effectively by managing the nearby passengers earlier. It is suggested that an additional function should be included in the socio-technical system to assist the evacuation process. From a systemic perspective, functional resonance could be mitigated if the Precondition 'nearby passengers evacuated' of the functions "Fight Fire Manually (First Aid)" and "Cool Boundaries" has an additional function to be provided by. The suggested function is identified as "Evacuate Restaurant Area". This is a preventive measure to add a dampening barrier to the socio-technical system.

The function "Evacuate Restaurant Area" is initiated when the Input 'fire observed' is met. This Input is provided by the "Detect Fire Initiation Manually" function. The Control of the function is 'fire spreads controlled' since the procedure for the evacuation depends on the availability of safe passages for the passengers. The Output of the function is to have the nearby passenger evacuated, same as one Output of the "Public Address to Muster Assessment Party".

Name of Function	Evacuate Restaurant Area
Description	
Aspect	Description of Aspect
Input	Fire observed
Output	Nearby passengers evacuated (same as "Public Address to Muster Assessment Party" function's Output)
Precondition	N/A
Resource	N/A
Control	Fire spreads controlled
Time	N/A

Table 60 Function - Evacuate Restaurant Area

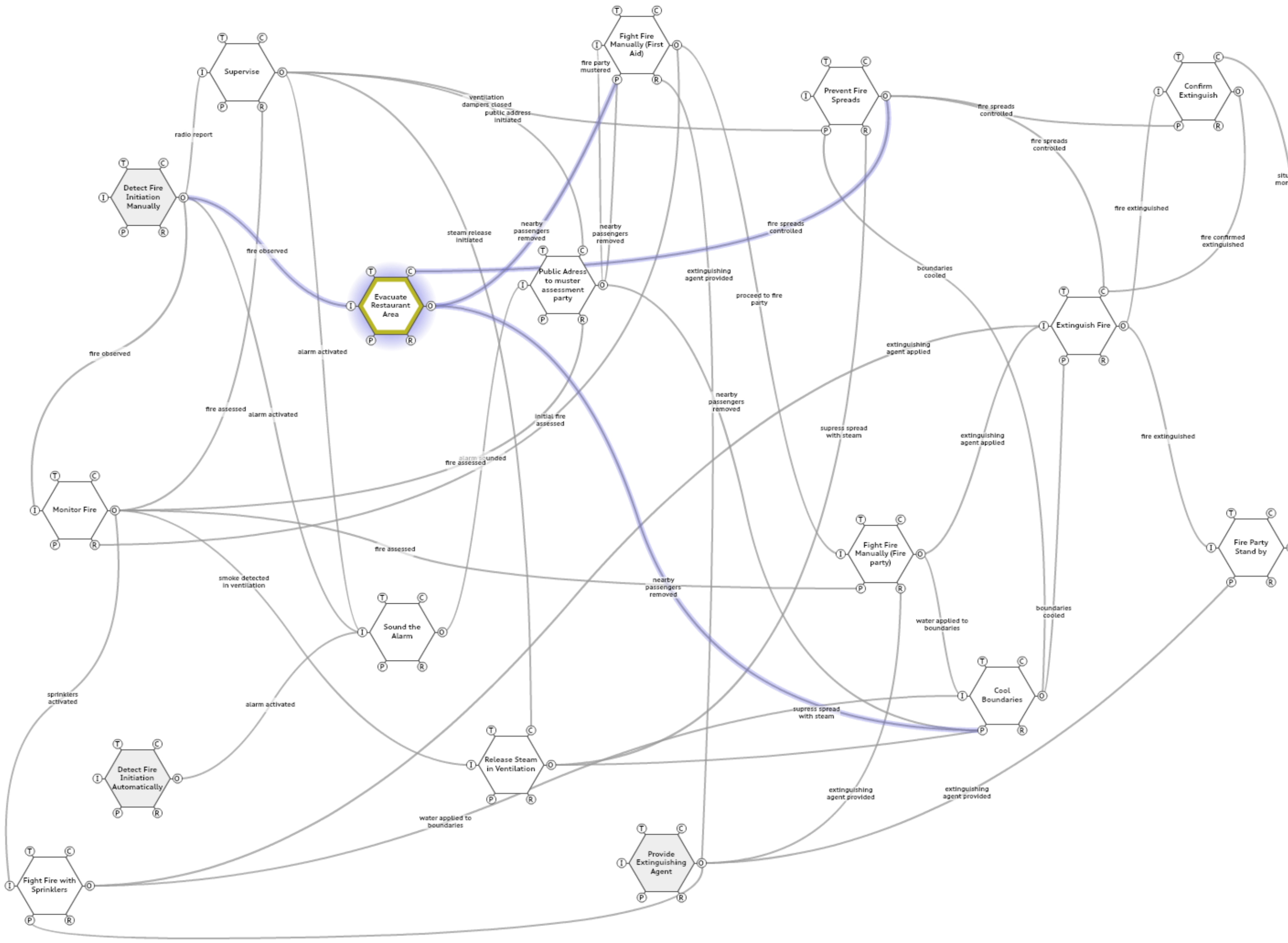

Figure 11 Graphical Respresentation 6

The figure bellow illustrates the socio-technical system in the FRAM software with the addition of the new function.

No additional functions need to be modified since the introduced function produces and requires existing Input, Control and Output.

Suggestion 2.

One method of improving the efficiency of the system is through facilitation. Facilitation refers to the strengthening of existing functions in contrast with the addition of new functions. The official investigation revealed that the crew did not have the information about the construction of the ventilation system. This in fact, reduced the performance of the "Prevent Fire Spreads" function because the precondition 'ventilation dampers closed' was not fulfilled. The delay in the responsiveness regarding that matter is attributed to the fact that the crew had limited knowledge regarding the location of the dampers. Even after the incident, the information was unavailable. This is an example of an organizational error that resulted in decreased responsiveness during this incident. The method of hazard elimination from this systemic perspective suggests that the "Supervise" function was overloaded to produce Outputs, since alarm activation, stream release initiation and public address initiation are also additional Outputs. The replacement of the system with an automatic system that is integrated to the fire detection system and does not require the human factor to interfere should be considered. This method of facilitation strengthens this barrier since technological functions are more reliable than the human element. Should cost be a limiting factor, the responsible organization should revisit the dampers plans and educate the crew members about the existing locations.

Suggestion 3.

During the fire-fighting efforts one crew member, part of the fire party, experienced discomfort when using an SCBA set. The SCBA set was later examined and found malfunctioning. This removes any doubt of the effects that acute stress could have on this individual's performance. No explanation was given regarding this malfunction. However, it is suggested that general maintenance should be prioritized and updated evaluations of the equipment should be frequent enough to proactively prevent this hazard. The emphasis on maintenance in a way constitutes the elimination of the hazard the malfunctioning SCBA set introduced to the function's performance. Even though it was not clear from the initial identification that "Maintain" should be included as a function, the functional resonance analysis suggests that general preconditions similar to this one could be included in every investigation to facilitate positive outcomes. The addition of every possible general precondition for each instantiation is beyond the analysis of this thesis. The addition of a general precondition as a function named "Maintain" could widen the scope of the investigation even further.

The function "Maintain" is identified as a general precondition to be included in the horizon of the socio-technical system. The function's purpose is to ensure the performance expected by the technological equipment use. In this instantiation, the variability lies in the

“Provide Extinguishing Agent” function. Therefore, the precondition ‘proper function of equipment’ will be added to the function “Provide Extinguishing Agent”. This will be provided as an Output of the function “Maintain”. Since it is important to maintain the necessary information in the model without unnecessary additions and since a general precondition is being identified, there is no need for Input, Preconditions, Control, Time and Resource. This is an organizational function.

Name of Function	Maintain
Description	
Aspect	Description of Aspect
Input	N/A
Output	Proper function of equipment
Precondition	N/A
Resource	N/A
Control	N/A
Time	N/A

Table 61 Function - Maintain (Maintenance)

The addition of this Output as a Precondition for the function “Provide Extinguishing Agent” requires a new description for this function.

Name of Function	Provide Extinguishing Agent and Fire-fighting Equipment
Description	
Aspect	Description of Aspect
Input	N/A
Output	Extinguishing agent provided
Precondition	Proper function of equipment
Resource	N/A
Control	N/A
Time	N/A

Table 62 Function - Provide Extinguishing Agent and Fire Fighting Equipment

The figure bellow illustrates the socio-technical system in the FRAM software with the addition of the new function

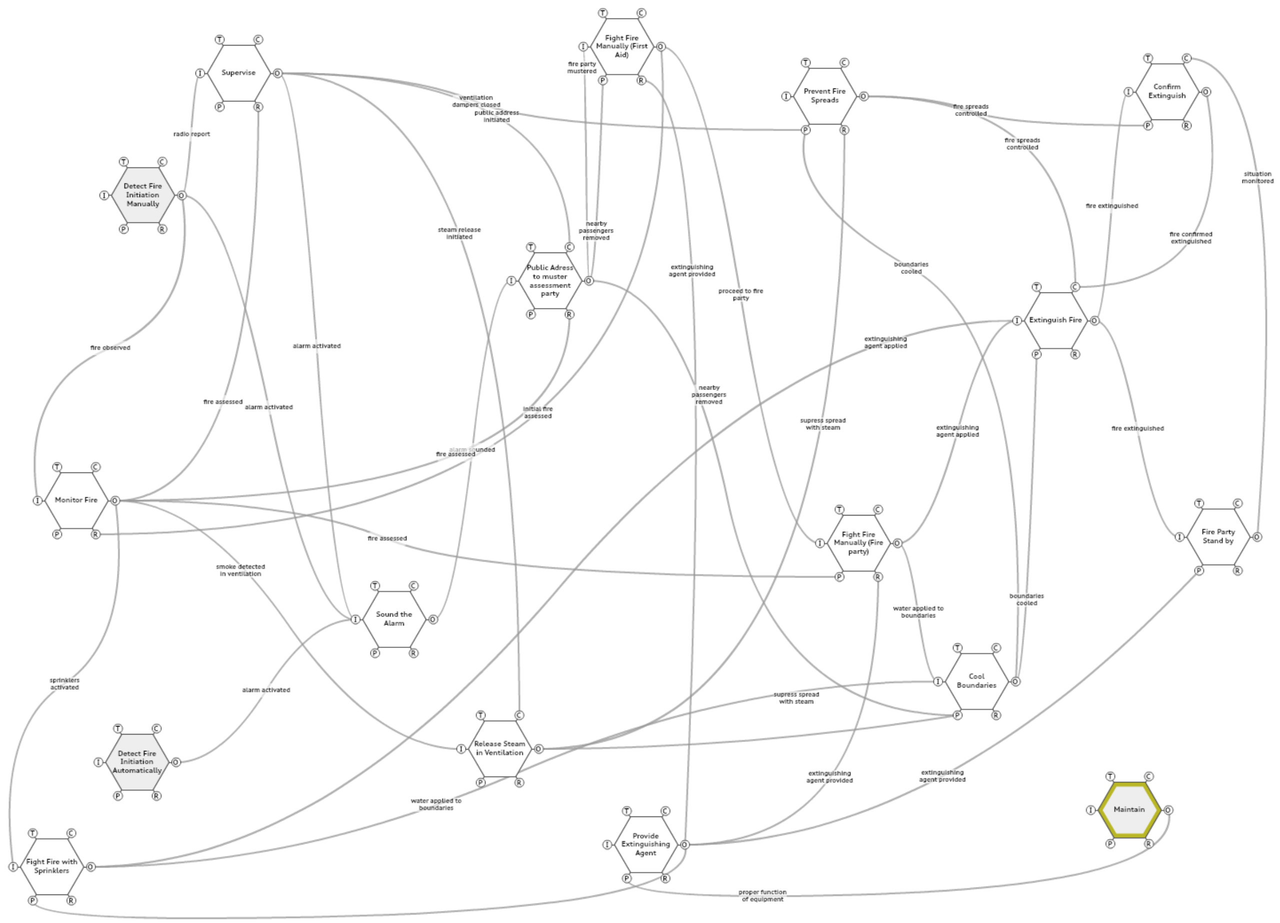

Figure 12 Graphical Representation 7

Suggestion 4.

The aim of functional resonance is to increase the resilience of a system, making it more tolerable to disturbances. The variability targeted by this suggestion is the upstream-downstream variability of the Output 'fire confirmed extinguished' of the function "Confirm Extinguish" that is provided as a Control for the function "Extinguish Fire".

The addition of a protective function to assist the socio-technical system that focuses on the better communication of the crew members is suggested. This function's purpose is to assist the "Prevent Fire Spreads" function by offering better communication regarding the possible locations the fire had spread. Since the fire was in the area of three deep fat fryers in this instantiation and the ducting was open above the location of the fire the possibility the fire would spread through the ductings was high. A function that accumulates collective the data from the fire assessment reports, from the initial to the on-going to provide accurate data to assist the fire party and the fire confirmation process is suggested. The function "Communicate" is identified as the needed function, referring to the communication needed between the separated crew members that investigate for fire spreads. The function "Communicate" is initiated when the Input 'public address initiated' is provided. The needed Resources for this function to perform as intended are the initial fire assessment and the fire assessment provided by the fire party. The Resources are provided by the functions "Fight Fire Manually (First Aid)" and "Monitor Fire" respectively. The function "Communicate", in this sense, is directly controlled by the function "Confirm Extinguish". The time the function stops performing is determined by the Output 'fire spreads controlled'.

Name of Function	Communicate
Description	
Aspect	Description of Aspect
Input	Public address initiated
Output	Evaluated data provided
Precondition	N/A
Resource	Fire assessed
	Initial fire assessed
Control	Fire confirmed extinguished
Time	Fire spreads controlled

Table 63 Function - Communicate

Changes should also be made in the identification of the "Fight Fire Manually (Fire Party)" and "Confirm Extinguish" functions.

The "Fight Fire Manually (Fire Party)" function's Control is the new provided state 'evaluated data provided' since the data partially control the fire party's performance.

Name of Function	Fight Fire Manually (Fire Party)
Description	

Aspect	Description of Aspect
Input	Proceed to fire party
Output	Extinguishing agent applied
	Water applied to boundaries
Precondition	Fire assessed
Resource	Extinguishing agent provided
Control	Evaluated data provided
Time	N/A

Table 64 Function - Fight Fire Manually (Fire Party)

The evaluated data provide a necessary Resource for the function "Confirm Extinguish" that is needed for the function to perform more effectively.

Name of Function	Confirm Extinguish
Description	
Aspect	Description of Aspect
Input	Fire extinguished
Output	N/A
Precondition	Fire spreads controlled
Resource	Evaluated data provided
Control	Situation monitored
Time	N/A

Table 65 Function - Confirm Extinguish

The figure bellow illustrates the socio-technical system in the FRAM software with the addition of the new function

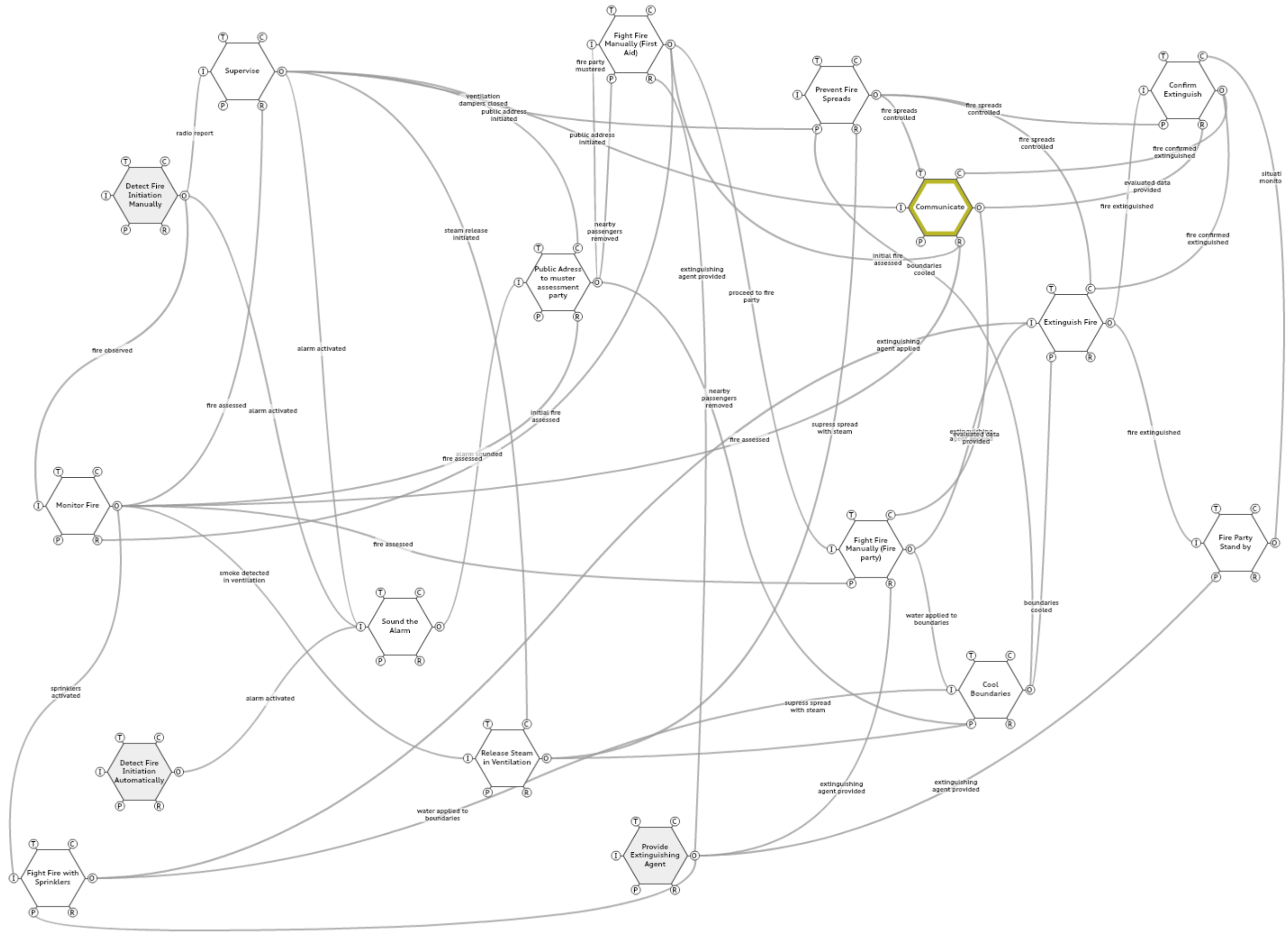

Figure 13 Graphical Representation 8

The socio-technical system with all the suggestions integrated is described by the following figure.

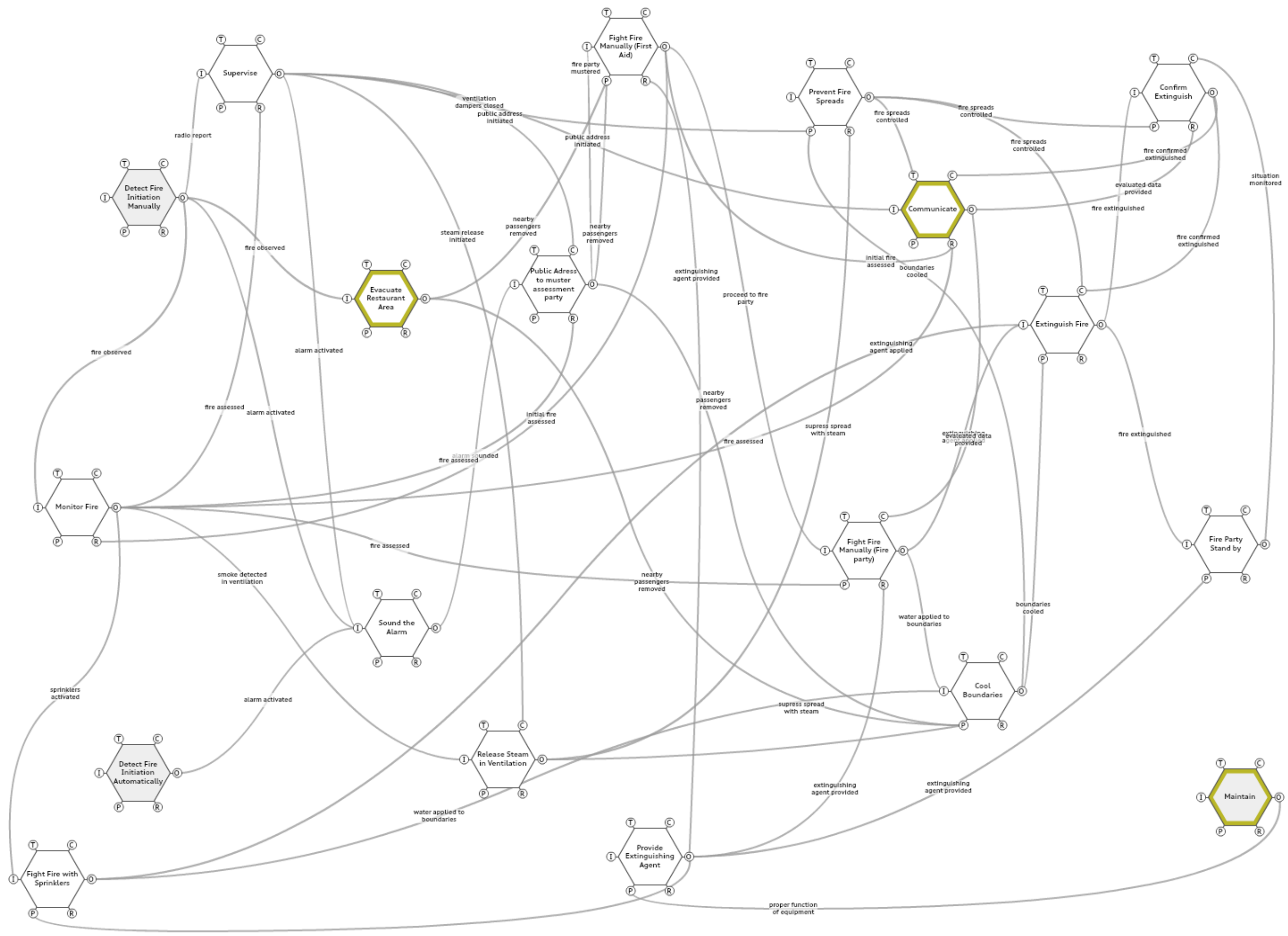

Figure 14 Graphical Representation 8

6. Conclusions

Learning from the past. A lesson can be learned from almost anything that occurs to us in our lives. Workplace incidents that result in near misses, property loss, or injuries are no different. Our past experiences can prepare us for future challenges. Incidents that have already occurred can provide a valuable lesson to learn, regardless of what went wrong. However, these lessons must be interpreted fully and completely in order to maximize their potential contribution to safety management in the future. By addressing -solely- the obvious causes, the investigator may lockstep the solutions he or she provides.

The shipping industry. The shipping industry realizes this fact and is increasingly investing in safety management to protect all valuable assets, be it human lives or the vessel herself. This requires deeper understanding of human limitations, such as stress and fatigue and system resilience both to reduce the frequency of incidents and to improve the emergency response, thus mitigating the damage, when disaster strikes. Many companies spend a lot of time, money, and effort to collect information regarding these types of incidents in order to find the root cause and try to prevent a similar event from occurring again.

International focus. These actions are not only funded by the private sector but also by global or national organizations as it ensures reduced risk in maritime operations. Their scope is to develop new and innovative tools, models and data for increased safety in shipping, respecting the harsh conditions and dangerous environment the industry involves. Through these actions, many lives have already been saved, as well as expensive assets that would have been otherwise lost.

State-of-the-Art. FRAM proposes a tool that has been proven valuable across different industries, as are the aviation industry, offshore drilling industry and others. In Chapter 4- State of the Art- of this thesis, there are several instances that prove this value. The same holds true for the application on incident investigation on fire accidents onboard ships, as of this study. FRAM has already been demonstrated in the shipping sector in certain instances other than emergency response onboard ship.

Different perspective. Incident investigation from a FRAM perspective does not look for a cause to be initiated but tries to understand what should have gone right. Then, the investigator analyzes the variability of each function and suggests the causes based on this analysis. It is possible to make suggestions on this analysis alone or even suggest additions to the system that may reduce future incidents. This can provide out-of-the-box solutions to increase the overall resilience of the system.

Applications. In this study, FRAM was attempted on two separate cases of well-known marine incidents involving fire onboard ship, in order to analyze the emergency response of the system. This involved a detailed understanding of how the incident occurred and of the events that took place. The required information was derived by MAIB, as a reliable source at no cost.

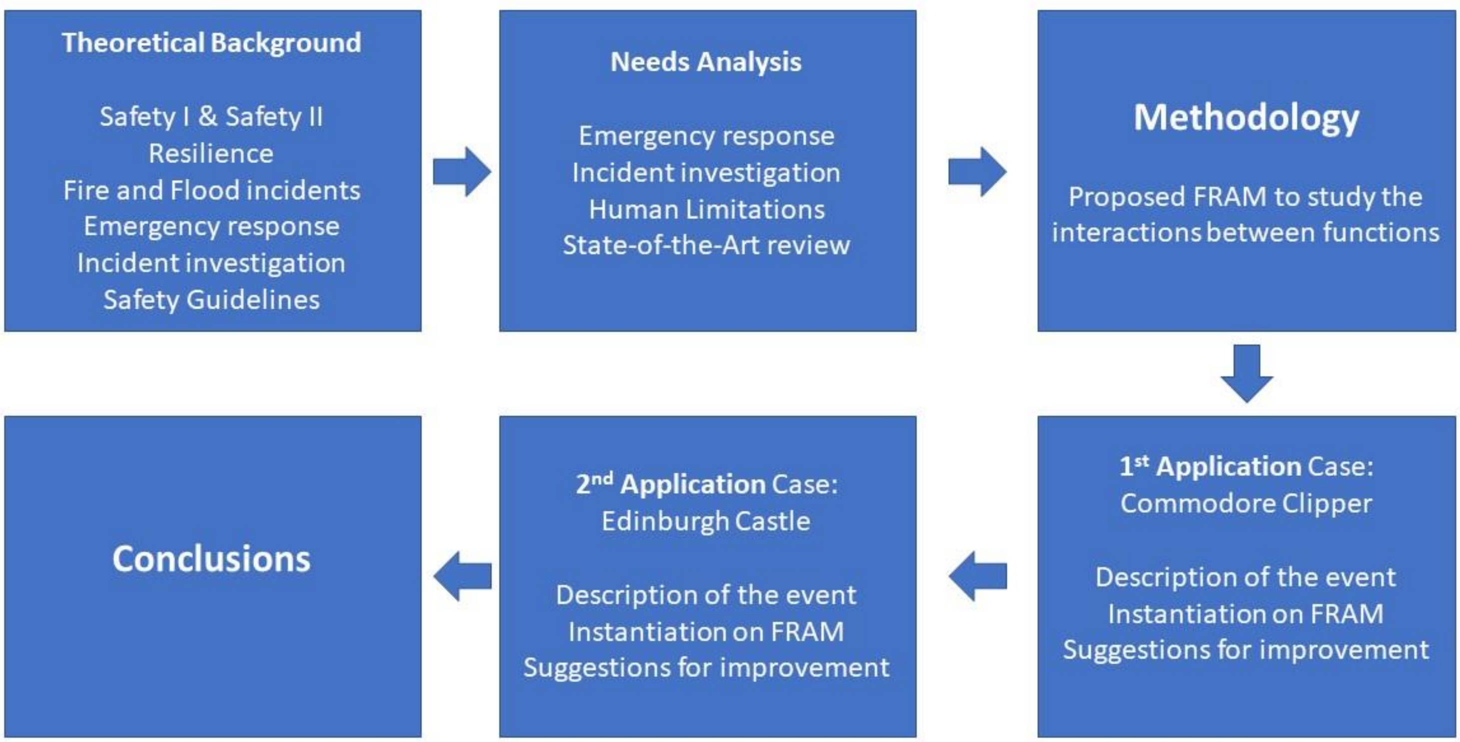

Figure 15 - Process of the Study

On Approach. Each event was individually analysed as two completely different case studies. First, the events were selected amongst hundreds of past incidents and handpicked based on 1) the level of detail of the available data and 2) the sequence of events that occurred. The first criterion was applied as most data through the research were incomplete for such and analysis, and the latter in order to demonstrate the capabilities of the method in greater detail.

This initial approach was proven valuable in later stages of the research, as the descriptions were complete, and the suggestions provided were more realistic to each situation. However, as with any suggestions in hindsight, the validation of the proposed solutions cannot be evaluated, especially in dynamic emergency response scenarios.

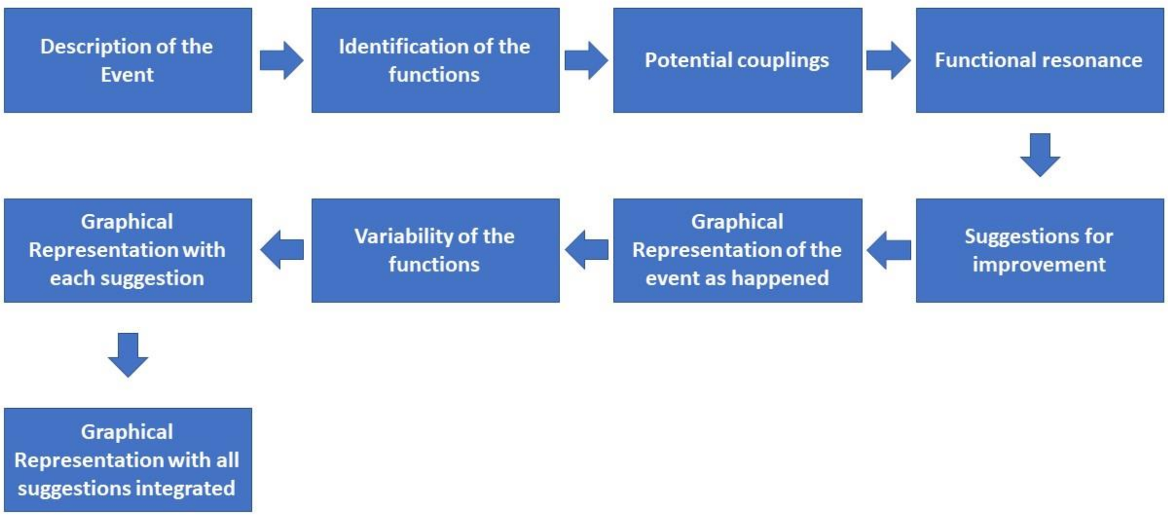

Figure 16 - Presentation of Methodology

For each incident, the functions that constructed each instantiation were identified according to the history of each event. Then, the functions were linked through their interdependencies and the instantiation was developed. This procedure was significantly more time consuming than other mainstream methods as fault-tree analysis. However, this effort could be reduced with the development of a single database involving frequently encountered functions. Even if every emergency response tells a different story with different events taking place, some functions are similar in most cases. A ready-to-use solution in such cases would be useful to the researchers performing this method.

Following the identification of the functions and couplings, the variability of each function was analysed. This was found the biggest comparative advantage, since it was observed that even functions with relatively small variability could greatly affect the outcome of a later function via functional resonance. These instances could be overlooked when analyzed with different methods other than FRAM, since they are the result of the interactions between two or more functions – something that commonly used methods do not take into account as does FRAM.

Finally, the instantiations were graphically generated. This was done using the available FRAM software tool. The software is user-friendly and provides useful, albeit limited, tools for the user. An order can be assigned to the functions to accurately depict the sequence of the events. However, this was only for visualization purposes as it provides no additional information.

Following this analysis, suggestions were provided based on the results. The suggestions were based on the principle of increasing the overall resilience of the system, described in Chapter 2.1.3 of this thesis. Four total suggestions were proposed for each of the two incidents – one for each way proposed in the literature (i.e. Elimination, Prevention, Facilitation and Protection).

The suggestions were then translated into added or altered actions and merged to the instantiation. For this, the instantiations need to be created from the initial stages, as each one depicts a different instance of the system. At the end of each case, an instantiation of what the system would look like with all the suggestions integrated is presented.

On FRAM. As any other method, applying FRAM has a learning curve. Currently, there are limited lectures given on the FRAM, limiting the potential to spread as an innovative method. After prolonged use of the tool, graphical representations become more easily understandable and thus, the efficacy of using the method increases.

The FRAM has the intrinsic feature of flexibility, since it is developed to depict different systems in different situations from different domains. This flexibility allows the researcher to stop at any level of details he or she is adequate for each analysis. During this study, the level of detail in the two cases was higher than needed for demonstration purposes.

The FRAM software offers a visualization tool for better understanding of the instantiation. However, providing an overly complicated visualization may hinder its purpose, since it can be quite hard to supervise something overly complicated. Thus, many important aspects may be overlooked, as are the interactions and the emerging properties. The visualization of systemic functional dependencies should provide a clear understanding of the system and FRAM provided a solid visualization tool with short learning curve.

The results of the analysis greatly depend on the researcher, as FRAM is a qualitative method. The lack of quantifiable results is not considered a shortcoming -as the purpose is to investigate the potential couplings- but may be a necessary step for the future of the method. This is described in the literature, as attempts to quantify the FRAM have been made, some of which with great success, hinting the demand. However, this needs to be demonstrated systemically since, until now, quantification is not integrated in the existing software (as of the course of this study).

A FRAM analysis is different from a risk assessment. FRAM is based on modelling the potential functionality instead of a specific representation. Thus, rather than analyse an assumed event path and look for the probability that single steps may fail or malfunction, a functional analysis tries to find the ways in which a situation can develop, and what the possible outcomes may be. Thus, the two methods cannot directly be compared but rather used complimentary to each other, as a complete set of solutions for the incident investigator.

On results. This study analyses the application of the FRAM in emergency response during fire incidents on board. The input data was derived from MAIB, which had already done a formal investigation of the event. The initial investigation did not apply the FRAM to provide the suggestions and did not take largely into account the emergency response. However, the sequence of events list was a valuable asset since it provided a clear picture of the event as happened.

The suggestions (1,2,3, and 4 for each case) were derived solely from the FRAM models. Collectively, they overlap with the suggestions made by the investigators, with some of the additions that are unique in the FRAM. The suggestions are discussed in detailed on the relevant Chapter (Chapter 5.1 and 5.2 – Suggestions for Improvement)

Table 66 - Commodore Clipper, differences in suggestions provided by the formal MAIB investigation and the FRAM analysis

MAIB Investigation	FRAM Analysis
Eliminate the hazard created by the high density of the vehicles. Leave 'paths' for easy access by the firefighting response team	Eliminate the hazard created by the high density of the vehicles. Leave 'paths' for easy access by the firefighting response team.
Courses on non-technical skills for crew members as a measure to increase responsiveness through better decision making and better situational awareness.	Courses on non-technical skills for crew members as a measure to increase responsiveness through better decision making and better situational awareness.
	Adding an additional fire patrol as a preventive measure for controlling fire spread at early stages.
	An additional Input to the function "Cut Air Supply" should be added to the system for redundancy reasons.

Table 67 - Edinburg Castle, differences in suggestions provided by the formal MAIB investigation and the FRAM analysis

MAIB Investigation	FRAM Analysis
Nearby passengers need to be evacuated before the firefighting process begins. The crew must ensure early evacuation of the area.	Nearby passengers need to be evacuated before the firefighting process begins. The crew must ensure early evacuation of the area.
Proper maintenance of the firefighting equipment.	Proper maintenance of the firefighting equipment.
	Replacement of the damper system with an automatic system that is integrated to the fire detection system and does not require the human factor to interfere should be considered
	The FRAM highlights the need for better Communication between the crew members. This is clearly depicted on the FRAM graphical representation and on the FRAM model. Better communication could dampen the effects of other neglected aspects of the procedure.

During the FRAM analysis, the initial suggestions were not considered, to reduce researcher bias. However, the MAIB report may have been structured in a way that made the suggestions more obvious, but this could not have been avoided.

The recommendations overlap with the tried and tested methodologies applied by formal and experienced investigators. Additional recommendations were made which cannot be evaluated properly until tested in real-life conditions. This evaluation goes beyond the scope of this study.

Thus, there are indications that the Functional Resonance Analysis Method can be used for obtaining additional lessons learned from past incidents and provide solid suggestions for future improvement and better safety management. However, this needs to be further demonstrated in larger scale and additional supportive tools and databases need to be developed to increase the efficacy and competitiveness of the method.

The additional recommendations may increase the system's resilience to an even greater extend than the initial investigation.

7. Suggestions for future research

Quantification. Through the study and in the existing literature, the need for quantification of the FRAM is dormant. Still, the method is applied beyond the academic circles and in multiple disciplines. This quantification effort may be even more difficult in the dynamic scenarios of emergency response and damage mitigation but could prove a valuable tool for more resilient systems. This should be attempted in accordance to the existing efforts of quantification of the FRAM in the shipping industry.

Large scale applications. Application of the FRAM in a large number of new or past incidents could improve the reliability of the method. In this study, two separate cases were analysed. This may provide indications that the method is valuable for evaluating the emergency response and increasing the resilience of a system, but more studies need to be conducted to prove the efficiency of the method. This requires large scale applications across different types of vessels and in different conditions, as well as a multiple of damage scenarios, as flooding or fire on special materials (flammable, etc).

Collective Databases. Although each instantiation may be different, since it depicts a different condition of the system, ship operations and emergency responses share commonly used functions. A collective database, preferably embedded on the existing software, could be timesaving and would increase the ease of use and thus, the efficacy of the method.

Machine Learning. Emerging and innovative technologies as Computer Science has recently proved a valuable tool for identifying links between different types of datasets. Machine learning algorithms could be developed to identify the potential couplings and reduce the risk of overlooking the overly complicated socio-technical systems.

Integration with other systems. Future research could attempt to integrate the FRAM with fire and flooding simulation software. This could possibly facilitate the qualification efforts since it will provide deterministic data on the Inputs, Outputs, Preconditions, Time, Resource, Controls, regarding the technological functions of the instantiations. Functions as “Sound the Alarm” and “Fire Sprinklers Turned on” could be coupled with an expected result and make the visualization clearer and more accurate.

8. References

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