Analysis of interdependencies within the fire fighting function on an offshore platform

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Abstract
Recent accidents such as the Macondo blowout actualize the issue of offshore safety. Accidents do occur in spite of actions taken to prevent them from happening. The energy-barrier philosophy is the governing principle within the Norwegian offshore industry. The paradox with that philosophy is that the construction of additional barriers may increase complexity within the system. Risk may be seen as an emerging property of complex systems, yet little attention is paid to complex interactions in barrier systems. The Petroleum Safety Authority Norway (PSA) has therefore raised the matter of dependencies within barrier systems during 2013 to increase awareness of their implications. The governing energy-barrier philosophy relies on linear reasoning and does therefore not provide tools for the interpretation of complex and non-linear interactions. Hence the purpose of this thesis is to apply a different method to interpret interdependencies in a barrier system on an offshore platform and then evaluate the application of that method. The purpose is also to see if the PSA prioritizes an essential issue.

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Summary
Major accidents at offshore installations initiate discussions concerning offshore safety management. The Macondo blowout in the Gulf of Mexico is a recent example of that.

In Norway the governing safety philosophy is the energy-barrier concept. It comprises the perception of risk as harmful energy that has to be contained and prevented from reaching a valuable target. Preventing and mitigating measures are then denoted as barriers. The barriers are constructed in a linear manner to form a defence in depth.

The paradox with the energy-barrier concept is that each added barrier increases the complexity in the barrier system. Another perception of risk is that it is an emerging property of complex systems. Such systems may be prone to have so-called normal accidents. These are accidents to be viewed as a property of the system. So, the intention to strengthen the defence may actually increase the risk level due to complex interactions within the system.

The Petroleum Safety Authority Norway (PSA) has raised the matter of dependencies within barrier systems during 2013. Prescriptive documents of today contain only short notes on interfaces within the barrier system. In addition to that, the governing energy-barrier concept does not provide tools for interpretation of interdependencies in the barrier system. Part of the purpose of this thesis was therefore too see if interdependencies in barrier systems constitute a problem that is essential to approach. It was concluded that there is a need to approach the issue and that the PSA prioritizes a relevant matter.

The purpose of this thesis was also to apply a method to interpret interdependencies in a barrier system on an offshore platform and then evaluate the application of that method. A literature study was conducted to outline the required characteristics of the method to apply to interpret dependencies. The method should promote a holistic perspective and account for non-linearity. It should also conform to the perception that risks may emerge due to complexity. The method chosen was the Functional Resonance Analysis Method (FRAM). This method was then applied in an analysis of the fire fighting function on an offshore platform. The fire fighting function was said to comply with standards and regulations.

The FRAM as it was applied in this thesis can be divided into two major steps. The first was the identification and description of functions regarded as relevant for the fire fighting function. The second step comprised the analysis of variability and functional resonance in instantiations of the model that was created during the identification of functions. The evaluation of the application of the method consisted of a discussion that treated the two major steps of the FRAM separately. The impressions from the application of the FRAM were also different with regard to the two parts. The analysis of variability and functional resonance was rewarding and easy to comprehend. The concepts of variability and functional resonance made the interpretation of complex interactions workable and possible to visualize. The identification phase was on the other hand characterized by difficulties and uncertainties. This step is important and lays the foundation for the analysis since the boundaries of the system are defined with regard to the identified functions. The main issue was the level of detail (degree of decomposition) in the descriptions of the functions. It is indeed a feature of a complex system that it is hard to model but the identification phase in the FRAM probably has to undergo further development. It is important that the model is reliable since it constitutes the foundation for the analysis of variability and functional resonance.

Sammanfattning

När större olyckor inträffar på offshore-anläggningar runtom i världen aktualiseras diskussioner kring rådande säkerhetsstrategier. Explosionen på plattformen Deepwater Horizon i Mexikanska golfen är ett exempel på en sådan händelse.

Den styrande principen för säkerhet i norsk offshore-verksamhet är energi-barriärkonceptet. I den filosofin betraktas risk som skadlig energi som måste hindras från att nå ett värdefullt mål. Barriärer konstrueras då för att förebygga olyckor och begränsa konsekvenserna ifall de ändå skulle inträffa. Barriärerna bildar ett djupförsvar som ska säkerställa funktionen även om en barriär fallerar.

Det finns en paradox med energi-barriärkonceptet och det är att varje barriär som tillförs ökar komplexiteten i barriärsystemet. Risk kan ses på olika sätt, förutom att se den som skadlig energi så kan man se den som en produkt av komplexitet. I takt med att komplexiteten ökar i ett system så ökar också risken för normala olyckor. Dessa olyckor klassas då som en egenskap hos systemet snarare än ett resultat av skadlig energi. Därmed kan alltså avsikten att stärka barriärsystemet leda till att risknivån ökar på grund av komplexa interaktioner inom systemet.

Petroleumtilsynet i Norge har lyft frågan om beroenden inom barriärsystem under 2013. Dagens standarder och riktlinjer innehåller endast korta notiser om beroenden inom barriärsystemet. Utöver detta så kan inte energi-barriärkonceptet användas för att tolka beroenden, det innehåller inte de analytiska verktyg som behövs. Därför är en del av syftet med detta examensarbete att undersöka ifall Petroleumtilsynets fokusering på beroenden är relevant. Slutsatsen rörande denna del av syftet är att Petroleumtilsynet fokuserar på ett väsentligt ämnesområde när de lyfter frågan om beroenden inom barriärsystem.

Syftet med detta examensarbete är också att tillämpa en metod för att tolka beroenden inom ett barriärsystem på en offshoreplattform och sedan utvärdera tillämpningen av metoden. En litteraturstudie genomfördes för att ta reda på vilka egenskaper som krävs hos en metod som används för att tolka beroenden. Metoden bör främja ett helhetsperspektiv och ta hänsyn till icke-linjäritet. Den bör också härstamma från uppfattningen om att risk kan vara en produkt av komplexitet. Metoden som valdes för tillämpning var Functional Resonance Analysis Method (FRAM). Denna metod tillämpades sedan i en analys av det aktiva brandskyddet på en offshoreplattform. Det aktiva brandskyddet antogs följa gällande föreskrifter.

FRAM tillämpades i två steg i detta examensarbete. Första steget gällde identifiering och beskrivning av funktioner som ansågs relevanta för det aktiva brandskyddet. I det andra steget analyserades variabilitet och funktionell resonans i tillämpningar av den modell som konstruerades när funktionerna identifierades. Intrycken från tillämpningen av FRAM diskuterades i två steg i enlighet med tillämpningen av metoden. Analysen av variabilitet och funktionell resonans var givande och förståelig. Variabilitet och funktionell resonans som begrepp möjliggjorde också tolkning och visualisering av komplexa interaktioner. Identifieringsfasen präglades dock av svårigheter och osäkerheter. Identifieringen är viktig och lägger grunden för den fortsatta analysen eftersom systemets gränser definieras relativt de identifierade funktionerna. Svårigheten var bland annat relaterad till detaljnivån (grad av reduktion) i beskrivningarna av funktionerna. Ett komplext system är svårt att modellera, trots det bör verktygen för identifiering av funktioner i FRAM fortsätta utvecklas. Det är viktigt att modellen är tillförlitlig eftersom den utgör underlag för analysen av variabilitet och funktionell resonans.

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Jens Åhman
Lund, New Year's Eve 2013

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1 Introduction

Safety on offshore oil and gas platforms has attracted attention during the recent years. The Macondo blowout in the Gulf of Mexico, where the rig Deepwater Horizon exploded, is one example of when severe consequences were encountered. There is also a recent example of when the absence of an ignition source was the only circumstance preventing a hydrocarbon release from igniting at the platform Snorre A (SINTEF, 2010). Another aspect appearing in the media is the petroleum exploration in the arctic regions. The environment is considered to be more sensitive in those areas. The arctic exploration is therefore a challenge to safety management, e.g. because of the more demanding surroundings in general. Hence there are both recent accidents and future challenges that actualize the issue of offshore safety.

Accidents such as the Macondo blowout initiate critical discussions concerning the current safety management strategies used in the offshore industry. These discussions are necessary for the development of the strategies and concern several issues. When are the weak spots induced during the lifetime of an offshore platform? Is it during the design of the platform, during the construction or during the operational phase? These are questions that imply that there is something wrong at the platform, e.g. bad design, wrongful installations or wrong procedures. But, on any given day in general, the platform actually functions as intended, which implies that everything is correct. So why do things get out of hand sometimes? Why are the efforts made today in the name of safety apparently not sufficient?

Nearly thirty years ago Perrow (1984) argued that certain systems are prone to have what he called normal accidents. These are accidents that are to be seen as a property of such systems. According to Perrow (1984) there are two concepts that characterizes a system that is prone to have normal accidents, these are complex interactions and tight couplings. Perrow's theory implies that accidents need to be understood as a result of interactions, relations and interdependencies in a system.

The concept of barriers is the governing principle of safety management on the Norwegian continental shelf today (PSA, 2013a). This means that design is considered safe when it complies with the philosophy of a defence in depth, with several layers that forms a protection against harmful energy (PSA, 2013a). Hence the concept of barriers is rooted in the linear thinking of symmetrical cause and effect relationships (Hollnagel, 2004).

Perrow (1984) argues that it is virtually impossible to construct a defence in depth without increasing complexity when a barrier is added. What Perrow (1984) says is basically that the construction of a defence in this manner increases the number of potential interactions between such barriers, i.e. complexity, and therefore also increases the potential for normal accidents.

The Petroleum Safety Authority in Norway (PSA) has raised the matter of barrier interdependencies as a focus area during 2013 in an attempt to increase the understanding of the implications of those dependencies (PSA, 2013b). Standards and guidelines applicable during the design of barrier systems are based upon functional requirements for each barrier. However, the matter of interdependencies in the barrier system gets little space. For each barrier there is a short note on interfaces with other barriers but it says practically nothing about the actual nature of the potential interdependencies.

As stated above, dependencies can be characterized with complex interactions and tight couplings. Hence they are features of system complexity. There are several voices that encourage the use of a concept that is different from the governing barrier concept when the purpose is to interpret dependencies. It is not sufficient to apply a linear method to approach the interdependencies in a system. The method used to interpret interdependencies in a system should be non-linear and stem from a systemic view on accident modelling (Dekker, 2011; Hollnagel, 2012; Perrow, 1984).

Summing up, according to Perrow (1984), the key to understand accidents lies in the interpretation of dependencies. There is a governmental wish for an increased understanding of dependencies but the governing concept is based on a linear reasoning of cause and effect. There is clearly a discrepancy between the wish for increased understanding and the attention paid to dependencies today. Furthermore, the governing concept of today is not capable of interpreting dependencies and to increase the understanding. There is a need to apply a different method that takes complex interactions and non-linearity into account.

1.1 Purpose

The purpose of this thesis is to investigate if interdependencies in barrier systems is an essential problem to approach. The purpose is also to apply a method to interpret interdependencies in a barrier system on an offshore platform and then evaluate the application of that method. The level of attention paid to interfaces and dependencies in prescriptive documents, e.g. NORSOK S-001 (2008), does not seem to embrace the assumption that risks and accidents are emergent properties of complex interactions and relations. Hence the purpose of this thesis is to approach this issue. The initial literature review will outline the rationale behind the choice of specific modelling method. The concluding evaluation will focus on the possibilities that the method provides for the analyst to interpret dependencies and the implications they may give rise to according to Perrow (1984). Impressions and reflections during the work process will also be discussed.

The purpose is operationalized into three major research questions to structure the work with this thesis:

- Are interdependencies in a barrier system a problem that is essential to approach?
- Which are the required characteristics of a method applied to interpret, problematize and discuss barrier interdependencies?
- What are the impressions from an application of a method that conforms to those requirements?

By answering the above questions it will be possible to present the theoretical background related to dependencies in complex systems and to discuss the results and impressions from the application of a method. It will also be possible to assess the criticality of the issue of interdependencies.

1.2 Limitations

Since the network of barriers on an offshore platform is extensive it will not be possible to perform a thorough analysis of the entire barrier system. Therefore this thesis is constructed as a case study focusing on one specific function within the system. The target for analysis will be the function with the purpose to fight fires, both automatically and manually. The choice of the fire fighting function as the target for the analysis is made because of the well-defined energy it is supposed to combat, namely fires and explosions. Threats from fires and explosions are tightly related to the extraction of hydrocarbons from wells deep underground. The fire fighting function is therefore a given function in the protection on an offshore platform. The author's background in fire protection engineering is also an argument for choosing the fire fighting function since it increases the probability of a good analysis.

Cilliers (2005) presents a set of attributes that characterizes a complex system, one of the attributes is that it is the interactions between components that defines the state of the system. This thesis focuses on interdependencies in a barrier system. Hence it is natural to state that the system modelling will be supported by complexity theory in the thesis. It means that the fire fighting function will be defined as open to the surrounding system environment (Cilliers, 2005). It also means that there are other ways to describe the system than the one chosen in this thesis, Cilliers (2005) puts it like this: "[…] the knowledge gained by any description is always relative to the perspective from which the description was made." (p. 258). The latter quote is indeed the core of this thesis since the idea is to adopt a certain perspective on safety. The method to be applied has a functional approach, this is crucial and means that the focus lies on how things happen instead of why (Hollnagel, 2012). The limitation differs from the traditional view on how to limit the space of analysis since it is about defining a starting point and letting the boundaries reveal themselves during the process. This will only be partially possible within the frames of this thesis. Hence it is necessary to control the boundaries in this thesis to ensure that the system will be interpretable. Interfaces to systems that are not explicitly part of the fire fighting function will be assumed to be static to their nature. The system may therefore be seen as semi-open to the surrounding system environment.

2 The Norwegian offshore industry

The Norwegian offshore industry has grown to be both the largest industry in Norway and the largest contributor to Norwegian welfare (Alveberg & Vaage Melberg, 2013). Interesting numbers describing the offshore industry in Norway can be viewed in Table 2.1.

Table 2.1. Numbers, Norwegian offshore industry (Alveberg & Vaage Melberg, 2013).

NOK 9000 billion net revenue since 1971.
76 productive fields as of today.
Total export of 225,14 million m^3 oil equivalents in 2012.
23 per cent of total gain in Norway in 2012.
7^{th} largest oil exporter in 2011.
3^{rd} largest gas exporter in 2011.

2.1 Safety within the Norwegian offshore industry

The governing authority for safety in petroleum related activities is the Petroleum Safety Authority (PSA). In the document *Principles for barrier management in the petroleum industry* (PSA, 2013a), the PSA states the following:

> As the HSE regulations make clear, barriers represent a key element in reducing risk on both offshore- and land based installations. Requirements for barriers are rooted in the "energy and barrier" perspective, which encourages a separation between hazardous energy and assets such as life, health, the natural environment and material facilities. (p. 4).

The PSA has also defined four different focus areas that will benefit from increased priority during 2013. One of the areas is barriers and one of their arguments for prioritizing this area is: "We in the PSA see a need for better understanding of the interaction between operational, organisational and technical elements in barriers." (PSA, 2013b).

Given the quotes above it is natural to conclude that barriers are the key elements in safety management in the Norwegian offshore industry.

2.1.1 Governing documents

The governing document for risk assessments is NORSOK Z-013 (NORSOK, 2010), in the section about general requirements for risk assessments the following is stated:

> Establishing the context covers all activities carried out and all measures implemented prior to or as a part of the initiating phase of a risk assessment process, with the intention of ensuring that the risk assessment process to be performed is
>
> a) suitable with respect to its intended objectives and purpose,
> b) executed with a suitable scope and level of quality,
> c) tailored to the facility, system(s), operations, etc. of interest,
> d) tailored to the required and available level of detail. (p. 19).

Item a) above is particularly interesting, given the PSA's intention to increase awareness of interactions in barrier systems, it is vital that the applied analysis method corresponds to the requirement in a) by paying enough attention to interactions.

The governing document on a technical level is NORSOK S-001 (NORSOK, 2008). The standard outlines the functional requirements for each barrier element in a barrier system. There are short notes on interfaces and dependencies but no information on the actual nature of those interactive features. Extensive information regarding the fire fighting functions is also given in the standard ISO 13702 (ISO, 1999).

3 Theoretical background

Statements and regulations from the PSA shows that the energy-barrier perspective is dominating within the offshore industry, the safety system on an offshore platform is therefore designed to conform to this philosophy. The question is if the governing energy-barrier principle is compatible with the PSA's desire for: "[…] better understanding of the interaction between operational, organisational and technical elements in barriers." (PSA, 2013b).

Interaction is the keyword in the quote above, but is the governing barrier principle based on an accident model that provides sufficient tools for interpreting dependencies within complex systems such as barrier systems? This chapter summarizes the theoretical foundation to this thesis. Firstly a description of the barrier concept is made, which is the current principle guiding safety work in the Norwegian offshore industry. Following is a presentation of attributes of complex accident models. The presentation of the different perspectives on how to deal with systems safety is intended to be polarizing and highlight the differences. A historical perspective on system dynamics modelling and an introduction to the method that will be applied in this thesis is given lastly.

3.1 The current philosophy

As stated in section 2.1, the use of barriers is central in Norwegian offshore safety management. Barriers can be either preventive or protective, either they prevent an event from occurring or they mitigate the consequences if it occurs anyway (Hollnagel, 2004). The underlying mentality is that harmful energy from a source of danger shall be prevented from reaching a valuable target. A common model used to explain the mechanisms of barrier systems is the Swiss cheese model (Reason, 1997). The model illustrates a defence in depth, which basically means a linear construction of multiple barriers to protect a defined target from harmful energy. The failure of one barrier is therefore no longer crucial for safety since another barrier stands in line to battle the energy (Reason, 1997). The Swiss cheese model highlights that there are weaknesses in each protective layer. The weaknesses are metaphorically described as the holes in a slice of Swiss cheese, hence the name of the model, allowing the harmful energy to pass through the slice of cheese. If the holes in the layers are aligned, the energy will be able pass through all barriers and reach the target (Reason, 1997).

The origin of barriers is the concept of harmful energy, meaning that energy is transferred in a way that causes damage to a target (Haddon, 1973). The target may then be protected by what Haddon (1973) denotes as countermeasures. These countermeasures range from the initial prevention of hazardous energy formations to re-establishment of the normal state. The energy release theory represents a linear reasoning of cause and effect. The basic principle of such causality is that one thing leads to another (Hollnagel, 2012). Hence an accident is said to be a result of a linear series of events (Hollnagel, 2004). The energy release theory has been developed into more complex linear models that expand the space of analysis by taking additional factors into account. These models are denoted as epidemiological models (Hollnagel, 2004). The additional factors are then added to the search for the root cause of a chronological series of events that leads to an accident (Hollnagel, 2004). Hollnagel (2004) means that four characteristics of epidemiological models generally separates them from simpler cause and effect models. These are performance deviations, environmental conditions, barriers and latent conditions (Hollnagel, 2004). Performance deviations refer to deviations in general without prejudice, the expression comprises e.g. technical failures and human errors. Environmental conditions pay respect to the surrounding environment, acknowledging that these may produce performance deviations. Barriers to prevent or protect from unwanted consequences, they may be applied throughout the entire progress of an accident. Latent conditions are defined as built-in features of a system that may lead to an accident at some time (Hollnagel, 2004).

The Swiss cheese is a kind of epidemiological model and is to be seen as a response to a need for more complex models than simple, sequential, models (Hollnagel, 2004). The holes in the barriers in the Swiss cheese model are examples of additional factors included to expand the space of analysis. In the model, they are considered to be active failures or latent conditions connected to each single barrier in the defence. These are the features that define the Swiss cheese model as an epidemiological model. Active failures are said to be human actions that are not safe and which affects safety directly. Latent conditions has a more organizational profile and is said to be due to a complex working environment according to Reason (1997).

3.2 An alternative approach

An important distinction between the energy barrier concept and the concept that is introduced in this section is the perception of what risk is. Where Haddon (1973) sees risk as an hazardous energy that has to be contained, Perrow (1984) views it as a product of complexity. These different views turns out to be interrelated since the paradox with the barrier concept is that each added barrier in a system may increase the risk in the system as a whole due to increased complexity (Perrow, 1984). Furthermore, on complexity related to defences in depth, Reason (1997) acknowledges that: "One of their more unfortunate consequences is that they make systems more complex, and hence more opaque, to the people who manages and operate them." (p. 8). So, if the governing principle makes the safety system more opaque, how can it be approached for interpretation? There is a need for another perspective on the mechanisms of a barrier system. This section presents thoughts on risks as a product of complexity and introduces the systemic accident model as an alternative to the current perception.

The issues of risks due to complexity is not new, Perrow (1984) discussed high-risk systems almost thirty years ago in the book *Normal accidents: living with high-risk technologies* and concluded that complexity is a natural attribute of present systems. In the book it is suggested that neither organizational nor technical safety measures can protect a system from what is called normal accidents (or system accidents as Perrow also denotes it). Instead, Perrow (1984) states that both organizational and technical safety measures increases the complexity and therefore also the probability of accidents that are to be viewed as normal. These are accidents that emerge due to a system's complex nature. Perrow (1984) introduces two concepts that affect the risk of normal accidents: Complex interactions and tight coupling. Those concepts might in combination produce a situation that is potentially disastrous. The meaning of complex interactions is, according to Perrow (1984), that failure of multiple components might have consequences that are impossible to foresee. Tight coupling means that a process is designed in a way that makes it impossible to handle a failed component separately, which affects the process safety in general. Hence the occurrences of normal accidents is an attribute of a system, it does not say anything about the frequency of such accidents (Perrow, 1984). This means that there is no prediction in time in the normal accident theory since it only states that certain systems are prone to having them. The Perrowian theory of normal accidents is almost thirty years old, yet the major principles guiding safety management today, e.g. Swiss cheese model, pays little attention to concepts as complex interactions and tight couplings.

The view on complex interactions is shared by Dekker (2011) who says that every additional layer from a defence in depth strategy increases the number of connections within the system significantly. Dekker (2011) also discusses the concept of complex interactions:

> Interactive complexity refers to component interactions that are non-linear, unfamiliar, unexpected or unplanned, and either not visible or not immediately comprehensible for people running the system. Linear interactions among components, in contrast, are those expected and familiar production or maintenance sequences, and those that are visible and understandable even if they were unplanned. But complex interactions produce unfamiliar consequences, or unplanned and unexpected sequences, that are either not visible or not immediately comprehensible. (p. 128).

Dekker (2011) states that the philosophy of hunting causes corresponds to a traditional view on analysis based on reductionism. The idea of this perspective is to analyse a system by reducing it, a system's behaviour will then be explained by the functioning of its parts (Dekker, 2011). Dekker (2011) means that an analysis method corresponding to the reductionist perspective narrows the space of possible interpretations. That is, because of the focus on the parts of the system rather than the interactions within the system. A reductionist perspective is not able to provide a complex interpretation and therefore it is not sufficient to apply such a simplifying method in complex cases (Dekker, 2011).

As stated above, epidemiological accident modelling involves active failures and latent conditions. It is though a reductionist model based on the assumption of linear cause and effect. Methods relying on this accident model have limited capacity when it comes to complex interpretations of a system. Instead, the applied method has to be based on a non-linear systemic accident model that focuses on tight couplings and complex interactions and sees the system as a whole. Lundberg, Rollenhagen and Hollnagel (2009) also promote a non-reductionist and holistic view that is in line with the views presented in this section: "To focus on the whole it is necessary to use a more systemic model that goes from the whole to different factors involved in accidents (top–down), rather than the other way around (bottom–up)." (p. 1310). This is a way to widen the space of analysis and enable complex interpretations.

An important distinction between epidemiological and systemic models is how accidents are characterized. In an epidemiological model an accident can be denoted as a resultant because of the explanation provided by reductionism and causality. In a systemic model accidents are seen as emergent instead of resultant. That is because the explaining principles in the epidemiological model are incapable of interpreting the mechanisms that generates the outcome (Hollnagel, 2012). A figurative comparison between resultant and emergent events generates a picture that permeates the disparities in general. A resultant implies that there are mechanistic arrows and forces that add up to a resulting event. An emergent phenomenon seems to be a product of a dynamically bubbling and ever-changing environment. In a way this is the picture of the fundamental difference between the perspectives cooked down to the bottom line. The adoption of a non-linear systemic model is therefore in line with the thoughts Perrow introduced almost thirty years ago, seeing normal accidents as an emergent product of complex interactions and tight coupling. Hence this thesis' focus on interpreting such complex interactions in the systems designed to guarantee safe operations.

3.3 System dynamics modelling

The system dynamics modelling that is necessary for the interpretation of dependencies in complex socio-technical systems can be traced back to the 1960s. Maruyama (1963) introduced the concept of the second cybernetics[1] which was a development of the concept of cybernetics that was introduced by Wiener (1948). Where cybernetics focuses on the counteraction of deviancy, the second cybernetics also involves amplification of deviancy. The difference is that the counteraction rely on negative feedback between elements in a system and the amplification on rely on positive feedback (Maruyama, 1963). Maruyama (1963) also states that the feedbacks in a system are mutual and therefore the reasoning of causality has to be questioned in favour of a non-linear reasoning, i.e. that a given condition may not result in a product with similar magnitude as the condition. These thoughts were presented half a century ago, yet the dominating concept has been of a linear nature since the second cybernetics were introduced (Hollnagel, 2012). With the conceptual framework of today, a method that corresponds to the philosophy of the second cybernetics would be denoted as dynamic and non-linear (Hollnagel, 2012).

Several methods has developed on a basis of the second cybernetics but in this thesis it is assumed to be sufficient to present the origin of the philosophy of system dynamics modelling. Hence no inventory of methods that corresponds to this philosophy is produced and only one of the methods will be introduced further. That is the FRAM (Functional Resonance Analysis Method), which is a method that is conceptually derived from the second cybernetics (Hollnagel, 2012).

3.3.1 The FRAM

The FRAM approaches a system from a functional perspective (Hollnagel, 2012). The concept of functional variability is central in the FRAM and it is acknowledged that this is a feature that is crucial within a system. The idea of the FRAM is therefore to identify performance variability that may induce functional resonance to be able to handle it in an optimal manner. That is, amplifying positive outcomes and dampening bad ones. Therefore the system's intended state is of interest and there is no initial need for an accident or a scenario to start applying the FRAM. The basic principle guiding the reasoning within the FRAM is that it is the same mechanisms that leads to both wanted and unwanted outcomes (Hollnagel, 2012). Due to the functional profile of the FRAM, the notion of components is replaced by the notion of functions in the syntax. The FRAM offers a step-by-step approach to the interpretation of complex systems.

The FRAM relies on four basic principles that pervades the way of thinking when applying the method (Hollnagel, 2012):

- The equivalence of failure and success. Meaning that the same mechanisms lead to either the desired outcome or an accident.
- The approximate adjustments. Everyday activities are always adjusted to the current conditions. These adjustments generate performance variability.
- All outcomes are to be seen as emergent instead of resultant. The latter implies that the outcome is a result of a reasoning based on causality.

[1] Cybernetics: "the science of communications and automatic control systems in both machines and living things." (Oxford Dictionaries)

- The use of functional resonance to describe relations and dependencies in a set of functions during a specified event.

3.4 Conclusion

The FRAM approaches a system with the intention of understanding everyday performance and has the system as the starting point for the analysis. Because of this there is no need for an accident or a scenario initially. The system is subject to analysis with regard to an actual scenario at a later stage in the process, it is referred to as an instantiation of the system's state given a defined context (Hollnagel, 2012). With regard to these features, there are several arguments for applying the FRAM. Firstly, it is applicable to a wide range of situations, both retrospective and prospective analysis. Secondly, it focuses on the description of the system rather than individual components. Finally, the setup corresponds to the requirements of a method that is to be applied to interpret dependencies in complex systems according to section 3.2.

4 Method

This chapter accounts for the approach in this thesis and an overview of the work process can be viewed in Figure 4.1. An initial literature review was performed to enable formulation of the background to the thesis and the research questions. The results from the initial review directed the focus during an extended literature review that aimed to respond to the research question concerning the required characteristics of the method to be applied. According to findings accounted for in chapter 3 the method to apply to interpret dependencies should stem from a systemic accident model and account for non-linearity and emergence. Hence the method chosen was a system dynamics modelling tool called FRAM, which is presented in *FRAM: the Functional Resonance Analysis Method* (Hollnagel, 2012). The application of the FRAM is accounted for in the upcoming section. In an effort to validate the findings a focus group, consisting of safety management experts from Det Norske Veritas (DNV), was given the opportunity to provide feedback for a preliminary version of the analysis. The discussion primarily comprised the identified functions that formed the model. The intention was to try the validity of the model from a reality based perspective influenced by experience and knowledge of systems similar to the one in this thesis. Since the purpose of this thesis was to evaluate the application of the applied method, the concluding discussion treated the impressions from the application, not the outcomes of the analysis. The outcomes of the analysis were instead accounted for in connection with the last step of the analysis.

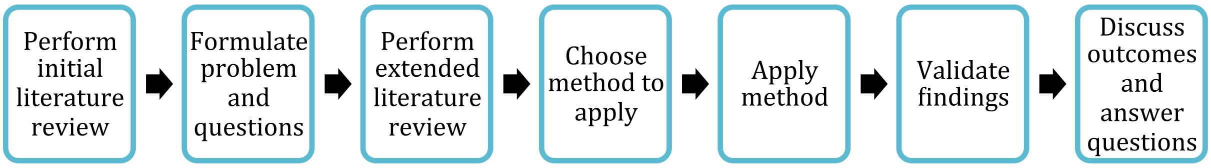

Figure 4.1. The work process in this thesis.

4.1 Application of the FRAM

The FRAM offers the methodology that guided the modelling of the system and the interpretation of barrier interdependencies. The rest of this chapter accounts for the application of the different steps in that method during the process of interpreting dependencies.

4.1.1 Identification and description of functions

The initial task in the application of the FRAM was to define the level of detail in the descriptions of the identified functions. It was therefore a question of defining what was to be seen as relevant during the analysis and laid the foundation for the upcoming work. The reasoning behind the level of detail in this thesis was qualitative and supported by ISO 13702 (ISO, 1999) and NORSOK S-001 (NORSOK, 2008). The analysed overall function was fire fighting and the limiting precondition for the identification of functions was that there was a fire in progress on the platform. The identification began from two functions that were seen as analytically relevant with regard to fire fighting, namely automatic fire fighting and manual fire fighting. All the functions were described on a level that communicated the intended purpose of each function. The identification continued until the occurrence of a function whose Output had no effect on a function within the system in question (Hollnagel, 2012, p. 59). The limitations in this thesis clearly affected the identification phase. It could have continued until the entire safety system was modelled but the modelling was constrained so that the model could be kept within the limitations. The functions considered as end points in the system either delivered a figurative Output or received an input from functions that lay outside the limitations of this thesis. This was to show that the system was open to the surrounding system environment.

To maintain consistency and facilitate navigation in the inventory of functions the so-called FRAM frame was used as it is presented in Table 4.1. The layout of Table 4.1 was used each time functions were represented. Explanatory tables adopted the layout of Table 4.2. The FRAM frame facilitated the identification of additional relevant functions by suggesting one outgoing and five ingoing threads that could be followed to identify additional functions. A description of the reasoning behind the aspects of each function was presented in conjunction with the frame for each function. The functional requirements related to a function were then briefly summarized in succession to the descriptions of the functions. Some aspects were not described initially due to their nature, e.g. Time requires that the function is put in a context but there is no sequencing of the functions in the FRAM model. Those aspects were denoted as N/A initially but were then discussed in the instantiations of the model. When the functions were discussed they were written in the following style: <Function>.

Table 4.1. The FRAM frame (Hollnagel, 2012, p. 56).

Name of function	
Aspect	Description of aspect
Input (I)	
Output (O)	
Precondition (P)	
Resource (R)	
Control (C)	
Time (T)	

The aspects in Table 4.1 is written with a capital first letter here, in line with the syntax in Hollnagel (2012, p. 47), this means that an input was categorized as Input, Precondition, Resource, Control or Time during the analysis. Every function had an Output that served as some sort of input to other functions. Explanations to the different aspects are provided in Table 4.2.

Table 4.2. The six aspects that describes a function (Hollnagel, 2012, p. 46).

Input (I)	That which the function processes or transforms or that which starts the function.
Output (O)	That which is the result of the function, either an entity or a state change.
Preconditions (P)	Conditions that must exist before a function can be carried out.
Resources (R)	That which the function needs when it is carried out (Execution Condition) or consumes to produce the Output.
Time (T)	Temporal constraints affecting the function (with regard to starting time, finishing time or duration).
Control (C)	How the function is monitored or controlled.

There was no specific scenario involved during the identification of functions (Hollnagel, 2012, p. 55). The couplings accounted for during the identification were therefore only potential couplings. Specific scenarios and actual couplings were accounted for in instantiations of the model at a later stage in the analysis (Hollnagel, 2012, p. 55). Twelve functions were identified as presented in Table 4.3. The potential couplings as they emerged during the identification are also listed for clarity. The list is in no particular order.

Table 4.3. Identified functions and potential couplings from/to other functions.

Function	Potential couplings from/to other functions (Aspect)
Fight fire automatically	Interpret fire detection (I)
	Automatically detect fire (P)
	Manually observe fire (P)
	Provide extinguishing agent (R)
	Supervise from control room (C)
	Communicate (C)
Fight fire manually	Activate alarm (I)
	Manually observe fire (I)
	Install and maintain (P)
	Provide extinguishing agent (R)
	Supervise from control room (C)
	Communicate (C)
Interpret fire detection	Automatically detect fire (I)
	Fight fire automatically (O)
	Install and maintain (P)
	Provide emergency power (R)
	Supervise from control room (C)
Automatically detect fire	Interpret fire detection (O)
	Install and maintain (P)
	Provide emergency power (R)
	Supervise from control room (C)
Manually observe fire	Activate alarm (O)
	Fight fire manually (O)
	Supervise from control room (C)
	Communicate (C)
Provide extinguishing agent	Start firewater pump (I)
	Fight fire automatically (O)
	Fight fire manually (O)
	Supervise from control room (C)
Supervise from control room	All functions (I)
	Communicate (P)
	Provide emergency power (R)
Install and maintain (background function)	Design of system and maintenance routines (O)
Provide emergency power	Interpret fire detection (I)
	Activate alarm (I)
	Interpret fire detection (O)
	Automatically detect fire (O)
	Activate alarm (O)
	Communicate (O)
	Install and maintain (P)
	Supervise from control room (C, O)

Function	Potential couplings from/to other functions (Aspect)
Activate alarm	Interpret fire detection (I)
	Manually observe fire (I)
	Supervise from control room (O)
	Install and maintain (P)
	Provide emergency power (R)
	Supervise from control room (C)
	Communicate (C)
Start firewater pump	Interpret fire detection (I)
	Activate alarm (I)
	Provide extinguishing agent (O)
	Install and maintain (P)
	Supervise from control room (C)
	Communicate (C)
Communicate	Fight fire automatically (I)
	Fight fire manually (I)
	Manually observe fire (I)
	Supervise from control room (I, O)
	Activate alarm (I)
	Install and maintain (P)
	Provide emergency power (R)
	Supervise from control room (C)

The identification of functions was a process based on assumptions and reasoning about which functions that could be considered relevant. The functions were then matched against the governing standards ISO 13702 (ISO, 1999) and NORSOK S-001 (NORSOK, 2008) to obtain knowledge of the design of the system. The list in Table 4.3 represents a summary of the FRAM model, more detailed descriptions are provided in chapter 5. A function can also be represented graphically. In a graphical representation, each function is represented by the hexagon in Figure 4.2. Each corner is dedicated to one of the six aspects in Table 4.1.

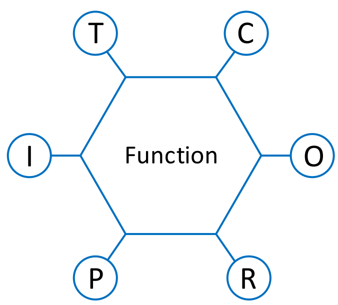

Figure 4.2. The graphical representation of a function (Hollnagel, 2012, p. 46).

The graphical representation primarily communicates the results in an instantiation of the model (Hollnagel, 2012, p. 55). A graphical representation of the potential couplings would not communicate anything other than that there are many potential couplings among the functions (Hollnagel, 2012, p. 55). However, a graphical overview of the identified functions without the potential couplings is presented in Figure 4.3.

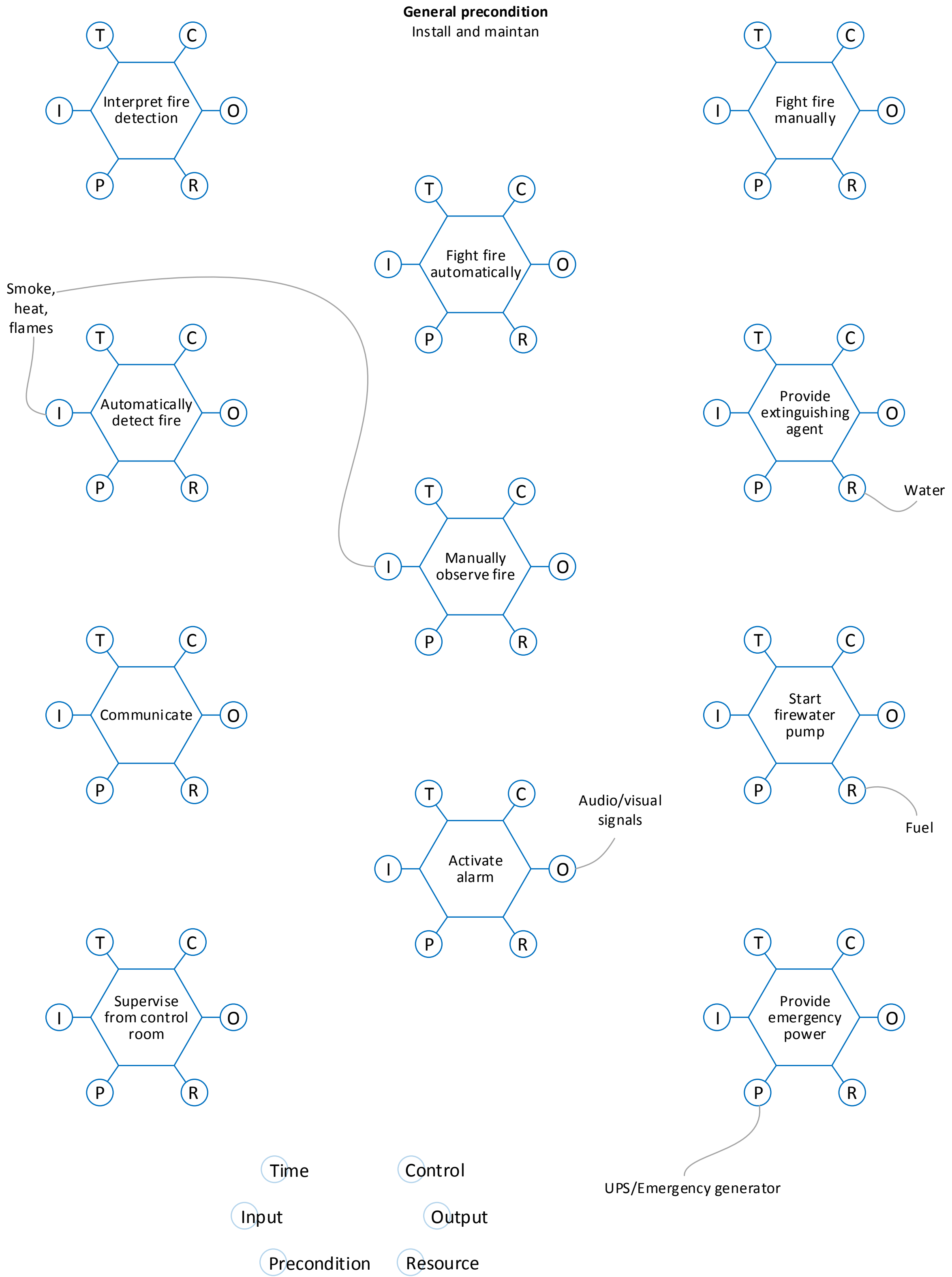

Figure 4.3. Identified functions represented graphically.

4.1.2 Variability of the functions

The variability concept is dual and comprises the performance variability of the function in question and the variability of the Output of that function. The variability of a function can be due to internal or external reasons. The variability of the Output of a function formed the basis for the concept of functional resonance by putting the function in a context. Functional resonance will be accounted for in the next section. The analysis of variability was performed backwards since the variability of a function itself was of no interest until the variability of the Output of that function had been confirmed (Hollnagel, 2012, p. 63). A thorough discussion on the potential variability would be time consuming and full of uncertainties so it was concluded that a reversed strategy was more efficient. With regard to this, the variability of the functions was analysed in the instantiations of the model.

A function is commonly categorized as technological, human or organizational (Hollnagel, 2012, p. 65). The identified functions are categorized in Table 4.4. Performance variability due to a functions adaption may be either internal, external or due to couplings with other functions (Hollnagel, 2012, p. 75).

Table 4.4. Categorization of identified functions.

Technological	Human	Organizational
Fight fire automatically	Fight fire manually	Install and maintain
Interpret fire detection	Manually observe fire	
Automatically detect fire	Supervise from control room	
Provide extinguishing agent	Activate alarm	
Provide emergency power	Communicate	
Activate alarm		
Start firewater pump		
Communicate		

The categorization in Table 4.4 gave a hint on how likely a function was to vary since the functions in the different categories were prone to vary to a different extent. Technological functions are mostly viewed as stable but may indeed vary due to e.g. software variability or physical degradation. Human functions may vary often due to several reasons related to the human nature and the variability tends to have rather significant volatility. Organizational functions do not vary as often as human but they also vary quite much when it happens (Hollnagel, 2012, p. 69). The topics of internal and external variability were quite easy to comprehend, internal variability stemmed from mechanisms inside the function and external from factors in the surrounding environment.

4.1.3 Functional resonance

The main question in this thesis is about the interpretation of dependencies. Therefore the effect of the variability of an Output of a function is of major interest. It is in the couplings to other functions that this variability manifests impact on the system as a whole. This aggregation of the variability of the Outputs of the functions is what constitutes the functional resonance within a system (Hollnagel, 2012, p. 77). Hence the internal or external reasons to the functions variability were of secondary importance. The explanation to why a function varied became interesting at first when the variability of the Output was confirmed (Hollnagel, 2012, p. 63). The variability of an Output was considered firstly during the analysis. The possible reasons to the variability of the function were then discussed if the Output varied.

At this point the impact of the performance variability of each function was put in a context and it was evaluated how the variability of the Output affected other functions. Depending on which aspect that received the varying Output from another function, the function in question was affected differently. The actual variability of the Output of a function may appear in different shapes due to the reason of the variability. Mainly four categories were used to characterize the actual variability of an Output of a function, these were as follows (Hollnagel, 2012, pp. 71-73):

- Timing and duration
- Force, distance and direction
- The Output as an object, e.g. the wrong object
- Ordering or sequencing of the Output, e.g. a function is bypassed

A description of the actual variability of an Output of a function was performed using an ordinal scale relating to the anticipated qualities of that Output, e.g. an Output was described as *too much* if it exceeded an expected quantity. If an Output was described with *too much* the variability belonged to the category denoted as *Force, distance and direction* (Hollnagel, 2012, p. 72).

If the Output of a function varied, then the varying Output affected the so-called downstream functions, i.e. the functions receiving the Output as input in an instantiation of the model (Hollnagel, 2012, p. 78). The functional resonance was analysed during the instantiations of the model that are accounted for in chapter 6.

4.1.4 Instantiations of the model

According to Hollnagel (2012, p. 75), couplings and variability should always be analysed with the support of an instantiation of the model. Hollnagel (2012, p. 36) also states that the approach in the analysis differs whether the task is an accident investigation or a risk assessment. The approach in this thesis was somewhat different since the construction of the FRAM model, i.e. the identified functions and the potential couplings, was neither based on an accident report nor a specific risk assessment scenario. The model was rather constructed on a regulatory basis, i.e. the functional requirements in standards and guidelines were the source for the construction of the model. The model was therefore to be seen as an inventory of functions relevant for fire fighting. This generic set up was then applied in instantiations of the model and only the functions that were involved in each instantiation were accounted for. The approach in this thesis was assumed to promote a construction of the model that was unconstrained by conditions during a specific case or scenario. According to Hollnagel (2012, p. 37), it is an advantage if the model can be constructed without such influence.

The model was applied in instantiations of three cases comprising two events as they happened and one risk assessment scenario. The application of the model was systematic and referred to the descriptions of each event. An analysis of the variability of the involved functions and their Outputs preceded a discussion on what functional resonance it induced in the system. Graphical representations of the instantiations then communicated the result of the analysis.

5 Identification and description of functions

The identification and description is based on ISO 13702 (ISO, 1999) and NORSOK S-001 (NORSOK, 2008). These two standards are the documents that are primarily referred to in the sections about fire fighting in the guidelines to the facilities regulations (PSA, 2012a). It is assumed that design and installation comply with them and the theoretical offshore platform is said to be a normally manned installation[1].

The construction of the model is independent of the starting point and therefore the FRAM provides no guidance on choosing a starting point. This thesis has fire fighting as the overall theme so it is vital to define a starting point that generates good preconditions for the identification of functions. The initial function should be analytically essential with regard to fire fighting (Hollnagel, 2012, p. 42). There are two functions with the objective to fight fires and therefore these are assumed to be good candidates to start with. The functions are automatic and manual fire fighting.

Table 5.1. Fight fire automatically

Name of function	**Fight fire automatically**
Aspect	Description of aspect
Input	Automatic or manual initiation of automatic fire fighting system
Output	Extinguishing agent automatically applied to fire
Precondition	Fire automatically detected
Resource	Extinguishing agent
Control	Monitor development, manual observation, communication
Time	N/A

The Output of the <Fight fire automatically> function described in Table 5.1 is automatic application of extinguishing agent against the fire. The Input is the initiation of the automatic fire fighting system, which leads to the identification of the functions <Interpret fire detection> and <Manually observe fire>. The Precondition is that the fire is automatically detected, hence the function <Automatically detect fire> is identified. Resource for the function is the extinguishing agent applied to fight the fire. The function <Provide extinguishing agent> is therefore identified. The Control aspect comprise monitoring and communication and the functions <Supervise from control room> and <Communicate> are also identified. Time is not described initially.

Automatic fire fighting system does not have to be installed on the entire platform. The requirement is that areas with major fire risks shall be covered, especially areas where hydrocarbons are present (NORSOK, 2008). An automatic fire fighting system can be of the following types (ISO, 1999):

- Deluge system
- Water-mist system
- Foam system
- Sprinkler system
- Dry chemical system
- Gaseous system

[1] The compliance to governing regulations may vary since the system in question is said to be complex but it is an essential simplification in this thesis. Everyday adaptions are though one of the basic principles of the FRAM.

According to ISO 13702 (ISO, 1999) the Fire and Explosion Strategy (FES) and governing standards shall guide the installation of the fire fighting function. The FES is defined as: "Results of the process that uses information from the fire and explosion evaluation to determine the measures required to manage these hazardous events and the role of these measures." (ISO, 1999, p. 3). The system shall be dimensioned to withstand the assumed fire load during a sufficient period of time. A possibility to manually activate the automatic fire fighting shall be provided (ISO, 1999).

Table 5.2. Fight fire manually

Name of function	**Fight fire manually**
Aspect	Description of aspect
Input	Initiation of manual fire fighting from automatic fire detection or due to manual observation of fire
Output	Extinguishing agent manually applied to fire
Precondition	Fire fighting tools available and maintained
Resource	Extinguishing agent
Control	Monitor development, communication
Time	N/A

The Output of the <Fight fire manually> function described in Table 5.2 is manual application of extinguishing agent against the fire. The Input comes either from <Manually observe fire> or an alarm that is activated, the function <Activate alarm> is therefore identified. The Precondition is that fire fighting tools are available and maintained, hence the function <Install and maintain> is identified. The Resource is again the extinguishing agent, thus the <Provide extinguishing agent> function. The Control aspect is fulfilled via <Supervise from control room> and <Communicate>. Time is not described initially.

Means for manual fire fighting include that any area shall be possible to reach with water from two hoses or monitors minimum (NORSOK, 2008). Manual fire fighting equipment comprise (ISO, 1999):

- Firewater monitors, i.e. water cannons
- Hydrants and hoses
- Portable fire fighting equipment

The equipment above shall be dimensioned to withstand the predicted fire load during a sufficient period of time (ISO, 1999).

Table 5.3. Interpret fire detection

Name of function	**Interpret fire detection**
Aspect	Description of aspect
Input	Fire is automatically detected
Output	Initiation of automatic fire fighting
Precondition	Detectors deployed and online
Resource	Power
Control	Monitor development, confirm detection
Time	N/A

The Output of the <Interpret fire detection> function described in Table 5.3 is initiation of automatic fire fighting. The Input comes from <Automatically detect fire>. The Precondition is that the detectors are deployed and functional, hence the governing function is <Install and maintain>. The Resource required for the function is power and that leads to identification of the <Provide emergency power> function. Control is ensured via the <Supervise from control room> function. Time is not described initially.

With regard to the overall task of fire detection this function comprises the actions taken of the fire detection system when a fire is detected. These actions are (NORSOK, 2008):

- Initiation of automatic fire fighting system
- Start of firewater pumps
- Activation of alarm to alert personnel and/or initiate manual fire fighting

The fire detection system shall be functional during a sufficient period of time and the status of the system shall be available in the control room (NORSOK, 2008).

Table 5.4. Automatically detect fire

Name of function	**Automatically detect fire**
Aspect	Description of aspect
Input	Automatic detection of smoke, heat or flames
Output	Fire automatically detected
Precondition	Detectors deployed and maintained
Resource	Power
Control	Monitoring
Time	N/A

The Output of the <Automatically detect fire> function described in Table 5.4 is automatic fire detection. The Input is the presence of smoke, heat or flames in the vicinity of a detector. The Precondition is that the detectors are deployed and maintained, thus the <Install and maintain> function. The Resource comes from the <Provide emergency power> function. Control is exercised via the <Supervise from control room> function. Time is not described initially.

Flame detectors are the primary kind of detector for use on a platform but other types are to be installed in special locations (NORSOK, 2008). The fire detection system shall be functional during a sufficient period of time and the status of the system shall be available in the control room. Each detector shall be identifiable in the control room (NORSOK, 2008). Deployment, maintenance and calibration of detectors shall ensure early detection (ISO, 1999).

Table 5.5. Manually observe fire

Name of function	**Manually observe fire**
Aspect	Description of aspect
Input	Manual observation of smoke, heat, flames
Output	Activation of alarm or both activation of alarm and manual fire fighting
Precondition	N/A
Resource	N/A
Control	Communication
Time	N/A

The Output of the <Manually observe fire> function described in Table 5.5 is either <Activate alarm> or both <Activate alarm> and <Fight fire manually>. The Input is a manual observation of signs of a fire, hence the <Manually observe fire> function. Control is ensured via the <Communicate> function. Precondition, Resource and Time are not described initially.

Table 5.6. Provide extinguishing agent

Name of function	**Provide extinguishing agent**
Aspect	Description of aspect
Input	Firewater pump running
Output	Firewater to automatic or manual fire fighting
Precondition	Install and maintain
Resource	Water
Control	Monitor development
Time	N/A

The Output of the <Provide extinguishing agent> function described in Table 5.6 is the pressurization of the firewater mains to <Fight fire automatically> or <Fight fire manually>. The Input comes from a firewater pump that is running, thus the <Start firewater pump> function is identified. The Precondition comes from the <Install and maintain> function. The Resource required is water. Control is established by the <Supervise from control room> function. Time is not described initially.

The main extinguishing agent discussed in standards is firewater (ISO, 1999; NORSOK, 2008). The supply system shall be dimensioned for the largest fire area and deliver sufficient pressure (ISO, 1999). The seawater inlet shall be monitored and measures shall be taken to prevent the system from being affected by e.g. marine growth (NORSOK, 2008).

Table 5.7. Supervise from control room

Name of function	**Supervise from control room**
Aspect	Description of aspect
Input	Information from all functions that has supervision as control feature
Output	Overview of the situation
Precondition	Communication
Resource	Power
Control	N/A
Time	N/A

The Output of the <Supervise from control room> function described in Table 5.7 is an overview of the situation for the operators. The Input is information from all functions. The Precondition is communication via the <Communicate> function. The Resource required is power, which is established via <Provide emergency power>. Control and Time are not described initially.

Supervision of the development of events is performed in the control room. Activities in the control room involve continuous monitoring of the status on the platform. For instance, any fire detection or activated alarm shall be visible in the control room (NORSOK, 2008).

Table 5.8. Install and maintain

Name of function	**Install and maintain (background function)**
Aspect	Description of aspect
Output	Design of system and maintenance routines

The Outputs of the background function <Install and maintain> described in Table 5.8 are the design of systems and maintenance routines. The function is guided by the Fire and Explosion Strategy (FES) on the platform and the governing regulations. This is a generic function that refers to the layout of the platform. With regard to fire fighting, the design shall reduce the consequences of a fire by ensuring that functions and equipment are appropriately available (NORSOK, 2008). This function is treated differently since it has potential couplings to all the other functions. Instead of accounting for it as a stable endpoint in the system it is involved in the model and may therefore be subject to variability.

Table 5.9. Provide emergency power

Name of function	**Provide emergency power**
Aspect	Description of aspect
Input	Fire is automatically detected or an alarm is activated
Output	Emergency power to consumers
Precondition	Installation and maintenance
Resource	Uninterruptible Power Supply (UPS) and emergency generator
Control	Monitor power supply
Time	N/A

The Output of the <Provide emergency power> function described in Table 5.9 is emergency power to consuming functions. The Input is a fire situation confirmed via <Interpret fire detection> or <Activate alarm>. Precondition comes from the <Install and maintain> function. Resources are the UPS and the emergency generator. Control is ensured via the <Supervise from control room> function. Time is not described initially.

Emergency power system shall be automatically initiated and shall be functional during a sufficient period of time (ISO, 1999). Emergency power may be provided by emergency generators and/or UPS, power may also be provided by cable from land or other installation where suitable (ISO, 1999).

Table 5.10. Activate alarm

Name of function	**Activate alarm**
Aspect	Description of aspect
Input	Fire automatically detected or manually observed
Output	Audio/visual alarms and signal to the control room
Precondition	Alarms installed and maintained
Resource	Power
Control	Monitor development, communication
Time	N/A

The Outputs of the <Activate alarm> function described in Table 5.10 are audio/visual alarms and a signal to the control room via <Supervise from control room>. The Input is either <Interpret fire detection> or <Manually observe fire>. Precondition comes from the <Install and maintain> function. The Resource is power, which is delivered by the <Provide emergency power> function. The function is controlled via <Supervise from control room> and <Communicate>. Time is not described initially.

Alarms are activated at fire detection, via manual call points and when a requested action fails to execute. An alarm shall be visible in the control room (NORSOK, 2008). The alarm should be audible and supported by visual signals in noisy areas (ISO, 1999). Power supply to the alarm system shall be ensured via the UPS (NORSOK, 2008).

It shall be possible to activate alarms manually via manual call points and these shall be deployed strategically in e.g. (NORSOK, 2008):

- Exits from relevant areas and rooms
- Escape routes
- Fire stations

The walking distance to a manual call point shall not exceed 30 meters (NORSOK, 2008).

Table 5.11. Start firewater pump

Name of function	**Start firewater pump**
Aspect	Description of aspect
Input	Fire is automatically detected or an alarm is manually activated
Output	Firewater pump running
Precondition	Pump installed and maintained
Resource	Fuel
Control	Remote or local monitoring
Time	N/A

It is assumed that the firewater pump is not running continuously. The Output of the <Start firewater pump> function described in Table 5.11 is that the pump is running. The pump shall start automatically at a fire detection or activation of an alarm according to ISO 13702 (ISO, 1999). If the automatic start fails, manual attempts shall be made either remotely or locally. The Input is therefore a fire situation confirmed via <Interpret fire detection> or <Activate alarm>. The Precondition is that the pump is installed and maintained, hence the <Install and maintain> function. The Resource is fuel to run the pump. Control is established via <Supervise from control room> or on-site monitoring via <Communicate>. Time is not described initially.

The pump system shall be capable of delivering firewater adequately and during a sufficient period of time to the largest possible fire area. The response time of the pump system shall be quick enough to ensure firewater supply. The pump shall start automatically at fire detection and if the connection to the control room is lost (ISO, 1999). It shall be possible to start the pump manually, either locally or from the control room, even if no other system is functional on the platform. The fuel tanks shall be large enough to keep the engine running for 18 hours (NORSOK, 2008). Fire detection in the pump room should not stop the pump. The pump should only stop if hydrocarbons are detected at the air inlet to the engine (ISO, 1999).

Table 5.12. Communicate

Name of function	**Communicate**
Aspect	Description of aspect
Input	From all functions that has communication as control feature
Output	Overview of the situation
Precondition	Communication facilities provided
Resource	Power and information
Control	N/A
Time	N/A

The Output of the <Communicate> function described in Table 5.12 is an overview of the situation. The Input comes from all functions that have communication as control feature. The Precondition is a functional communications system, ensured via the <Install and maintain> function. The Resources are power via the <Provide emergency power> function and information. Control and Time are not described initially.

Equipment for internal emergency communication shall be provided to ensure means of communication between personnel and to control room (NORSOK, 2008). The power supply to the communication equipment shall be independent (ISO, 1999).

6 Variability, functional resonance and instantiations

The model that was constructed in the previous chapter shall now be applied in three different instantiations. The two initial instantiations are based on reports on accidents involving fire at offshore platforms on the Norwegian continental shelf. The third instantiation is a risk assessment where the scenario is an unwanted outcome from a function due to performance variability. The accidents and the scenario are briefly summarized with a focus on the performance of the fire fighting function before an instantiation is developed. The instantiations comprises the analysis of variability and functional resonance as well as a graphical representation. Conclusions regarding the instantiations of the model are drawn in section 6.4.

6.1 Fire in exhaust duct from main generator at Åsgard B

The fire occurred on 15 Oct 2005 and took place due to an ignited oil leakage in a heat exchanger connected to one of the generators. The fire detection system failed to discover the fire and the alarm was initiated by a manual observation. Available fire fighting tools were designed in a way that resulted in an insufficient application of firewater against the fire. The crew improvised and managed to control the fire and extinguish it anyway (PSA, 2006).

6.1.1 Description of the event

The generator had been shut down due to the discovery of oil spills in the vicinity of the exhaust duct. A scaffold was in construction with the purpose to gain access to investigate the source of the leak. Abnormal smoke emerging from the exhaust duct was observed by the fire watch during the construction of the scaffold. Flames were also observed shortly after the observation of smoke and at this point the alarm was activated via a manual call point. The alarm initiated mustering of personnel and activated the emergency response team. The first attempt to fight the fire was with a powder extinguisher and it failed. The firewater monitor was manned and engaged shortly after the first extinguishing attempt, it was then discovered that the water did not reach the fire as intended. The crew then had to lay out hoses to provide water to a portable firewater monitor that could fight the fire from a second front. The hose extension took 19 minutes to perform. The application of firewater was now sufficient and the fire was extinguished. A minor emergency shutdown was initiated during the event and it did not include the start-up of the emergency generator (PSA, 2006).

6.1.2 Variability of the functions

The analysis will focus on functions that produced a varying Output. It will show if it was the potential variability that became actual or variability due to a varying Output from an upstream function.

The automatic fire detection did not detect the fire but it is not made clear why the flame detectors did not discover the flames. The fire occurred outdoors and external factors such as wind might have affected the detectors ability to see the fire. The first sign of the fire was smoke emerging from the exhaust duct and flames were observed shortly after that. Due to the early observation of smoke it could also be that the manual observation was faster than the detection system. This would imply that there was nothing wrong with the detectors. They just needed a more significant sign of the fire before they were able to detect it. This explanation suggests that the omission of the automatic fire detection was due to the variability of the manual observation and that the quick discovery of the fire was faster than the detectors. Alternative explanations are that the detectors were not installed in an optimal manner or, as stated above, that external factors such as wind affected their ability to detect the fire.

The early manual observation is an example of an adaption to the circumstances that led to an early activation of the alarm and therefore also the early initiation of manual fire fighting. The early detection may have been triggered by the discovery of oil spills. This abnormality may have increased the fire watch's attention.

The Output of the manual fire fighting function was subject to variability since the fire was hidden from the fixed firewater monitors. The fire fighters had to extend the water supply with six hoses before a portable monitor could be engaged from another angle. The reason to the variability of the Output was external variability due to the design of the fixed firewater monitor system. The fixed monitor system could not cover all the relevant angles and the required position of the portable system demanded a very long hose.

With the support of the reasoning above it is possible to identify the couplings related to Time during the event. These are accounted for in the graphical representation of the instantiation in Figure 6.1.

Table 6.1. Variability of Outputs during the fire at Åsgard B.

Function	**Output**	**Variability of Output**
Automatically detect fire	Fire automatically detected	Detection omitted. Probably because manual observation was quicker or because of weather.
Manually observe fire	Activation of alarm or both activation of alarm and manual fire fighting	Earlier activation of alarm and manual fire fighting due to increased attention.
Fight fire manually	Extinguishing agent manually applied to fire	Powder extinguisher was too weak to put out fire. Firewater monitor pointed in the wrong direction and the fire was hidden from that point of view. Portable monitor needed six hoses to be placed correctly which is too long. The hose extension was slow and took 19 minutes.

6.1.3 Graphical representation

The instantiation of the fire fighting functions during the event at Åsgard B is represented graphically in Figure 6.1.

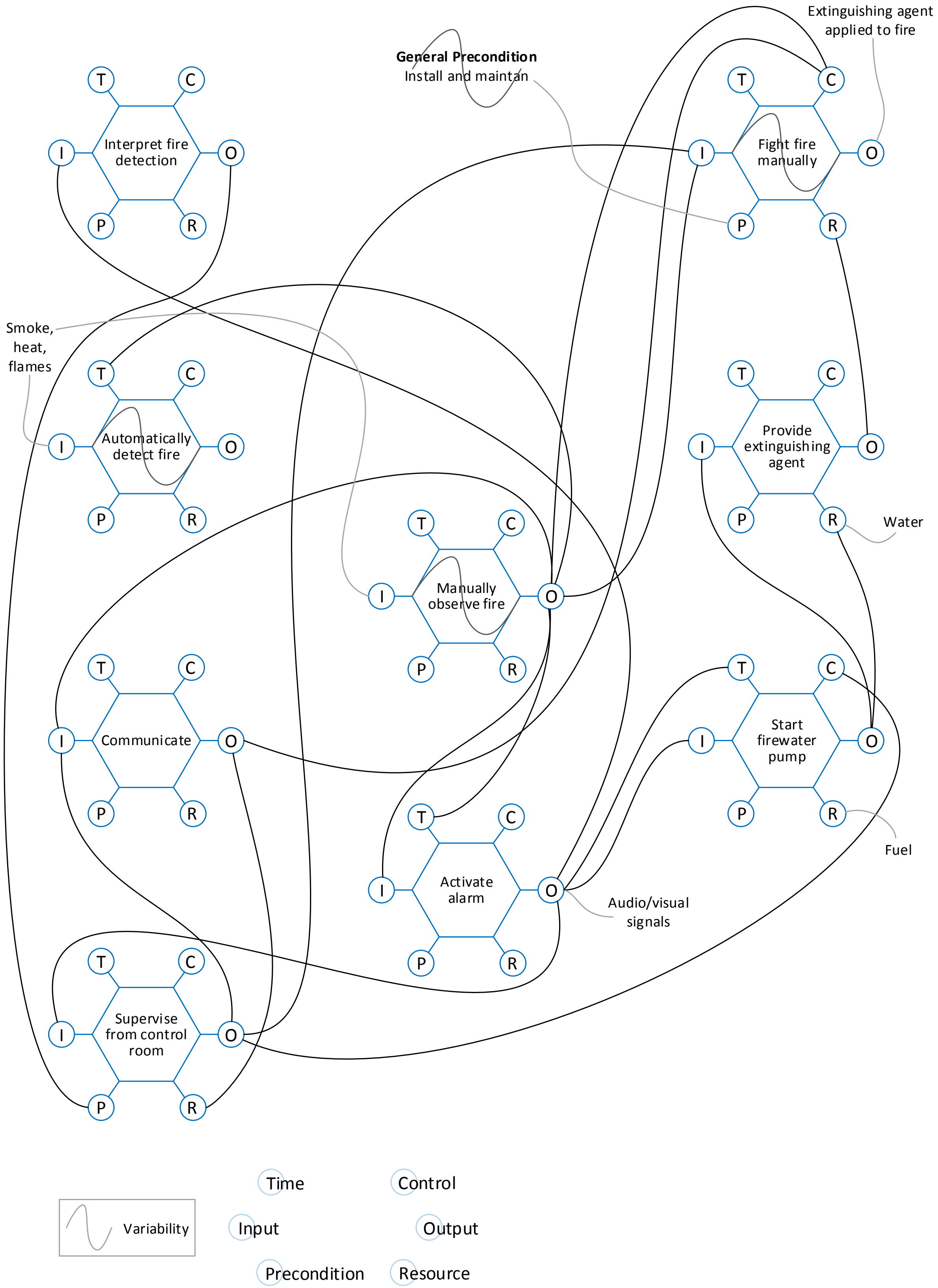

Figure 6.1. Instantitation of the firefighting functions during the fire at Åsgard B.

6.2 Fire at vent stack connected to the compressors at Valhall PCP

The event occurred on 13 July 2011 and took place due to an ignition of flammable gases emerging from a vent stack connected to compressors. The gases were ignited by smouldering particles that were produced by a fire in a crane engine room. The particles were transported via the exhaust duct out in the open and the wind directed them towards the vents (PSA, 2012b).

6.2.1 Description of the event

The breakdown of the cooling system and a following heat detector malfunction in a crane engine resulted in a fire in the engine room. The crane operator was able to extinguish the fire but smouldering particles had already exited the exhaust duct. The muffler was designed to prevent smouldering particles from exiting the engine but did not do so. The particles were blown by the wind towards a vent stack where flammable gases from the compressors on the platform were released into the atmosphere. The gases were ignited and produced a fire where the flame height reached three meters and above. The alarm to the control room was delivered manually via telephone. The compressor was then stopped which led to an increased volume of flammable gases emerging from the vents. Even higher flames followed due to the increased volume of gases and this time a flame detector detected the fire. The flame detection led to a shutdown of the normal power supply on the platform. No automatic means of fire fighting were installed in the area and the situation was considered to dangerous to send in fire fighters. The fire was finally extinguished by water cannons mounted on a ship (PSA, 2012b).

6.2.2 Variability of the functions

The fire at the vent stack was manually observed and the control room was notified by telephone. The fire at the vent stack was also automatically detected at a later stage when the flames increased in height. The air intake to the crane engine was shut and the engine stopped when the fire was automatically detected. This was due to the emergency shutdown when the power supply on the platform also was shut off. When the engine stopped, the crane operator opened the door to the engine room to investigate why it stopped and discovered the fire. This shows that the fire in the crane engine room was manually detected, but not until the flames were detected automatically.

Manual detection of the fire in the engine room was delayed due to variability in the automatic detection function in the engine room. The heat detection was omitted in this case, which made the crane operator believe that everything was normal and he continued working. The crane engine should have been shut off automatically on detection of increased temperatures. This can be characterized as an automatic fire fighting function, which was also omitted. The automatic flame detection responded to the fire at the vent stack roughly four minutes after the manual call to the control room, which seems late given the circumstances. The crane operator had just secured the crane when emergency shutdown occurred and the shutdown made the crane inoperable. Any emergency operation that could have been initiated during those four minutes could have been affected when the power suddenly was shut off.

Table 6.2. Variability of Outputs during the fire at Valhall PCP.

Function	Output	Variability of Output
Automatically detect fire	Fire automatically detected	Detection was omitted in the crane engine room due to a malfunctioning heat detector. Detection of the flames at the vent stack was too late in relation to the manual alarm.
Manually observe fire	Activation of alarm or both activation of alarm and manual fire fighting	The fire at the vent stack was detected as required and the alarm call was made.
Fight fire manually	Extinguishing agent manually applied to fire	Omitted because the situation was considered to dangerous. None of the vents had flash back protection.

6.2.3 Graphical representation

The instantiation of the fire fighting functions during the event at Valhall PCP is represented graphically in Figure 6.2.

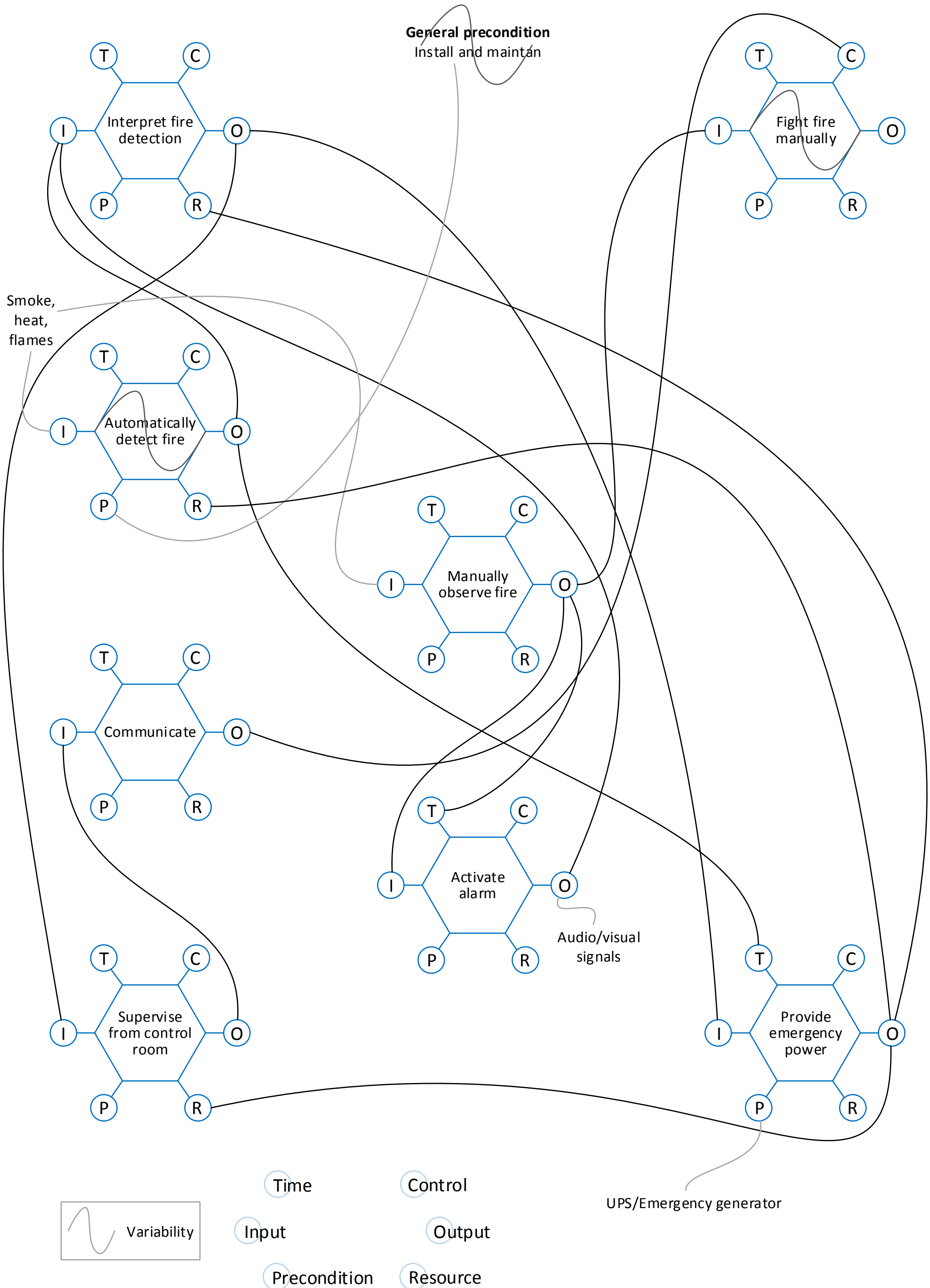

Figure 6.2. Instantitation of the firefighting functions during the fire at Valhall PCP.

6.3 Risk assessment of a scenario

Automatic fire detection and automatic fire fighting are omitted in both cases above. Therefore it is interesting to create a scenario where these functions are partaking. The scenario involves the induction of performance variability in a function that is connected to the automatic means of fire fighting to see how the system responds. The scenario is created in a way that allows investigation of the performance of the overall fire fighting function when its sub functions are subject to variability. It is an imagined situation and it is not described according to an actual design of the system in question. The situation is rather based on assumptions of how the variability of the Output of a function may contribute to functional resonance within the system.

6.3.1 Description of the scenario

The scenario is preconditioned by the fact that there is a fire in an area were automatic fire detection and fire fighting is installed, e.g. the process area (ISO, 1999). It is then assumed that the function intended to interpret the signal from the detection system is subject to variability and activates the alarm too late. Suppose that the delayed interpretation of the signal is indicated in the control room, i.e. it is communicated that the detector has been activated but no signal has been forwarded in the system. According to ISO 13702 it shall be possible to manually activate the automatic means of fire fighting (ISO, 1999). Suppose that the control room activates the alarm and instructs an operator to initiate the automatic fire fighting. The operator is quick and activates the system almost immediately. The start-up of the firewater pumps is delayed since it is not initiated until the control room sounds the alarm. The pump engine starts at the third automatic start attempt and the pressurization of the fire water mains is ensured. At this time the fire fighting system has been active for a while and has come to suffer from a loss of pressure. The application of firewater in the area was therefore not sufficient initially. The applied water has evaporated and this has created a damp and very hot atmosphere in the area, i.e. no manual intervention is possible. The fire is extinguished within a minute when the pressure is properly re-established.

6.3.2 Variability of the functions

Variability is induced in the function that shall interpret fire detection and forward a signal to the control room and the alarm system. The variability of the Output of this function was that it was delayed, or even omitted. Since the function is of technical nature, the variability was not expected in the way it had been if it were characterized as e.g. human. This is because technical features are generally viewed as stable and not subject to frequent variability (Hollnagel, 2012). Probable reasons for the variability are either internal or external since it is stated in the scenario that the detector functioned as intended. The cause for the variability need not to be investigated here since it is a risk assessment of a bigger picture, but possible causes may include software malfunction or physical degradation of the function (Hollnagel, 2012).

The varying Output from the function set to interpret the fire detection resulted in varying Inputs to other functions. The fire detection had to be interpreted in the control room, which rendered a manual activation of the alarm. The automatic fire fighting had to be initiated manually after instructions from the control room. The firewater pumps received the start-up signal later than it should have. In addition, the function with the task to start the pumps was subject to internal variability that led to a delayed start of the pumps. No manual intervention was possible during the loss of pressure due to dangerous conditions in the process area. Hence the manual fire fighting functions ability to adapt was nothing worth in this situation.

The fire was finally extinguished automatically regardless of the variability in the fire fighting function as a whole.

Table 6.3. Variability of Outputs during the risk assessment scenario.

Function	**Output**	**Variability of Output**
Interpret fire detection	Initiation of automatic fire fighting	Interpretation of the signal from the detector was too late, or even omitted.
Supervise from control room	Overview of the situation	Supervisor had to manually interpret the fire detection and manually activate the alarm. The automatic interpretation was missing in the sequence.
Fight fire manually	Extinguishing agent manually applied to fire	Omitted because the situation was considered to dangerous or too late because of the delayed activation of the alarm.
Start firewater pump	Firewater pump running	Too late due to several start attempts.
Provide extinguishing agent	Firewater to automatic or manual fire fighting	Too weak due to loss of pressure in firewater mains. Normalized when pressure re-established.
Fight fire automatically	Extinguishing agent automatically applied to fire	Too weak initially because of insufficient volume of firewater. Normalized when water supply re-established.

6.3.3 Graphical representation

The instantiation of the fire fighting functions during the scenario is represented graphically in Figure 6.3.

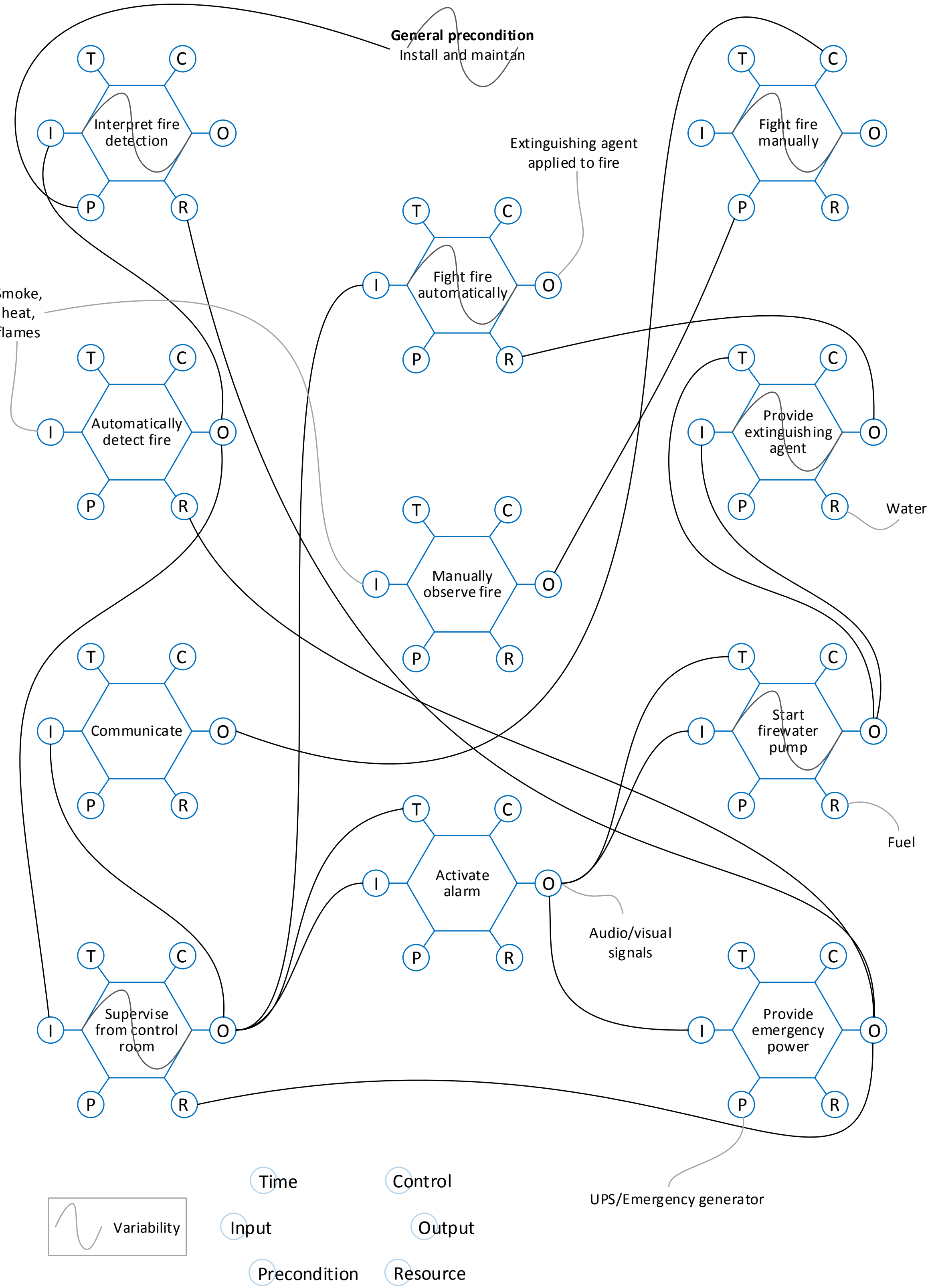

Figure 6.3. Instantitation of the firefighting functions during the scenario.

6.4 Conclusions from the instantiations

Human functions are subject to variability frequently. The instantiations of the events show that human adaption was necessary in both instantiations concerning past events. It was then a question of positive performance variability because without it the situations would not have been controlled. In the event at Valhall PCP the automatic detection function rather could have interfered with manual efforts due to the delayed detection and the following emergency shutdown. The complex interactions seem to increase when redundancy counteracts efforts that are initiated at an earlier stage.

Quite surprising it is the variability of Outputs from technical functions that are significant. If the unwanted outcomes or the absence of outcomes depend on internal or external variability is up for discussion. The technical functions that are included in the overall fire fighting function on an offshore platform are not that complicated. Therefore it is more natural to assume that variability is due to external factors such as installation and maintenance. These are human or organizational background functions that affect the abilities of technical functions.

Organizational functions are not identified or described explicitly since fire fighting is characterized as work as done, not work as imagined (Hollnagel, 2012). The function comprising installation and maintenance describes general preconditions for the performance of the safety system. The <Install and maintain> function was though identified as an important function because of the impacts of its varying Output in all instantiations. Paying respect to background functions is therefore assumed to be essential.

Functional resonance is a property of the system due to varying Outputs in all instantiations. It is interesting to see how the functional resonance propagates in different directions within the system. A slight variability of an Output of a given function may induce variability in several other functions. These may in turn deliver a varying Output. Hence the non-linearity of the interdependencies is visualized during the analysis. The functional resonance also generates couplings that were not identified as potential, for instance when the <Interpret fire detection> function was bypassed and the detection had to be interpreted in the control room during the risk assessment scenario.

The concepts of variability and functional resonance catch the essence of complex interactions within the system. The actual couplings that emerge during the instantiations are though uncertain to some extent. They are a product of the interpretation of a scenario and therefore subjectively motivated. There may be arguments for a different interpretation that renders a different instantiation but this is one of the exciting features of the modelling of complex systems (Cilliers, 2005).

7 Discussion

The approach in this thesis is quite simple:

1. Identify required characteristics of a method applied to interpret dependencies
2. Apply a method that conforms to those requirements
3. Evaluate the application of that method

This chapter comprises discussions on the outcomes of the analysis and reflections on the analytical process in this thesis. The discussion on the approach in the literature study and the findings it rendered is rather short and will be accounted for initially.

7.1 Reflections on the theoretical background

The fundamental work for this thesis was to identify the required characteristics of a method used to interpret interdependencies in a barrier system. The approach was quite polarizing and aimed to highlight differences between different concepts. The major distinctions were accounted for and may be summarized as follows: Decomposition vs. Holism, Linearity vs. Non-linearity, Resultant vs. Emergent and Energy vs. Complexity. No deeper introduction was provided to the notions of active failures and latent conditions in the Swiss cheese model. These are complex features of that model and it could have been fairer to describe them as such. The approach was though assumed to be sufficient with regard to the purpose of this thesis.

According to Perrow (1984), dependencies can be characterized by the concepts of complex interactions and couplings. The severity of these features then defines the risk level in the system as a product of complexity. It is quite remarkable that the issue of complex interactions has not been attended to more extensively. The concept can be traced back to the same era as the energy release theory, the latter then underwent a development that later led to the barrier concept. Perrow's introduction of the normal accident theory seems to have been an event that brought the concept of complex interactions back on the agenda. The awareness of the implications of complex interactions has probably increased ever since, but there seem to have been difficulties to operationalize the concept. These difficulties were present during the application of the FRAM in this thesis and will be discussed below.

7.2 Outcomes of the analysis

Safety management within the Norwegian offshore industry has developed in the spirit of the Swiss cheese model. This model represents a linear thinking of symmetrical cause and effect relationships, meaning that it does not provide sufficient analytical tools for interpretation of dependencies. The construction of a defence in depth that conforms to the philosophy of the Swiss cheese model may rather increase the complexity in the safety system. Hence it also increases the potential for normal accidents. The question was if interdependencies in barrier systems constitute a problem that is essential to approach. This is also a question of whether the PSA focuses on a relevant issue when they prioritize the matter of interdependencies in barrier systems.

The outcomes of the analysis show that complex interactions within the barrier system may give rise to unanticipated interdependency. The relatively small case study in this thesis indicates that it is essential to approach the issue of interdependencies in barrier systems. The governing safety management philosophy does not attend to this matter sufficiently. When a safety system is designed, each barrier in a defence in depth is metaphorically represented by a slice of Swiss cheese. The holes in the slices are quite well evaluated, i.e. certain properties, such as size and position, have been defined. For instance, if the barrier is of technological nature, then the properties of the holes are defined by failure frequencies or probabilities. In an illustrative event tree the slices of cheese would be the nodes and the properties of the holes would be represented by the probability of failure assigned to each node. This approach is analytically valuable to some extent since the reliability of technical functions indeed is important. Though, it does not account for the relationships between the holes in a slice or between holes in different slices. These relationships can be viewed as the interdependencies in the barrier system. Knowledge of the properties of the holes has to be considered insufficient if risk is assumed to be a product of complexity. This is the issue that has been approached in this thesis.

The FRAM analysis illustrates the implications of the interdependencies in the system during two events as they happened and one risk assessment scenario. The analysis of interdependencies in the barrier system is therefore based on an event that occurs during the operational phase. The design of the barrier system is though, as previously stated, based on linear thinking. The outcomes of the analysis imply that it may be necessary to involve an assessment of interdependencies already in the design phase. Enhancement of the ability to manage interdependencies is therefore not considered a matter of choosing between philosophies. It is rather about incorporating the assessment of interdependencies in the safety management strategy at an early stage.

The incorporation of interdependency assessment is considered a way to reduce negative effects of redundancy and to make interactions anticipated rather than unanticipated. Hence it is believed that greater attention to interdependencies promotes consistency of actions taken during an event. The instantiation of the event at Valhall PCP showed that human and technological functions might counteract each other in unanticipated ways. Such interactions may create potentially dangerous situations when the conditions for an on-going manual intervention suddenly change. The instantiations of the two events also showed that human variability was necessary during the efforts to control the situation. Perhaps it is time to start relying on the human ability to adapt instead of implementing technological functions in excess. At least the technological functions should be controlled when manual actions are initiated since they may obstruct positive human performance variability.

The matter of interdependencies is considered to deserve the prioritization from the PSA. However, it is interesting to note that is a focus area during the year of 2013, this shows that the industry and the governing body are slow to adapt. The perception that complex interactions have impacts on the performance of a barrier system is approximately thirty years old, at least.

7.3 Evaluation of the application of the FRAM

It was concluded early in the work process that a thorough FRAM analysis cannot and should not be performed by a single person. This is also acknowledged by Hollnagel (2012, p. 53). It was then decided to focus on the essentials of the methodology to be able to evaluate the application of the FRAM generally rather than to scrutinize each step of the method.

It was the explicit wish in this thesis to focus on interdependencies in a system and some difficulties were experienced during the process. The difficulties were not related to the comprehension of complex interactions and couplings. The variability and functional resonance were tools that allowed interpretation of them within the frames of the FRAM. The difficulties were rather related to issues that arise when a system is defined as complex.

Hence it was not a problem to analyse the modelled system, the problem was rather related to the construction of the model via the identification of functions.

7.3.1 Identification and description of functions

Hollnagel (2012, p. 42) states that the identification of functions may start with any function, anywhere in a system. This means that the level of detail (treated as synonymous to degree of decomposition) in the description of the first function preconditions the identification of other functions. The boundaries of the analysis were therefore strongly depending on the level of detail in the descriptions. If the descriptions of the functions are used as a tool to identify additional functions, as was the case in the analysis in this thesis, then the boundary of the system (or the overall function) is defined with regard to the functions. To use the FRAM language: The variability of the Output of the <Identify and describe the functions> function induces variability in the function <Set the boundaries for the analysis>. A more detailed description of the functions simply narrows the space of analysis since the boundaries tend to move inward as the Outputs of the functions becomes more detailed. If the task is to perform a detailed analysis of a system with the same boundaries as a less detailed analysis, then it is probably required that the boundaries are set in advance. On the other hand, if the level of detail is too superficial with regard to boundaries that are set in advance, then the system will probably miss essential functions when the identification is done. However, the system would no longer be defined as open to the surrounding environment if the boundaries were set in advance. This contradicts one of the basic attributes of a complex system (Cilliers, 2005).

The identification had to be constrained in this thesis. Therefore the modelled fire fighting function can only be viewed as semi-complex. Hence the concept of decomposition was present during the application of the non-linear systemic method in this thesis. The limiting condition was of course that the model had to be workable. It is though important to verify that the chosen level of detail really adds something to the bigger picture. To trivial descriptions tend to render a quite obvious analysis that requires no previous knowledge of the workings of a risk assessment.

The tight coupling between the descriptions of the functions and the boundaries of the system was an issue during the application of the FRAM. It is stated in Hollnagel (2012, p. 59) that the identification should come to a halt when a function is identified as stable with regard to the system. But this was a highly subjective task. With a little imagination it would have been easy to continue the identification in excess. Variability can probably be found in any function and this means that the built-in stop feature in the FRAM model is rather weak. This is though one of the challenges with the modelling of a complex system and as Cilliers (2005) stated; the description of a system always rely on the individual describing it.

The FRAM was applied with the precondition that it was a fire in progress somewhere on the offshore platform. Hence the primary approach was a risk assessment but the model that was constructed with the support of this condition was then tried in three instantiations. It is therefore a slight modification of the FRAM since it is stated that it should always be applied with a specific purpose (Hollnagel, 2012, p. 36). To state that there is a fire in progress somewhere on the platform is not assumed to be specific enough. Perhaps it was the approach in this thesis that was too generic but the difficulties are believed to be present whenever a risk assessment is to be performed in general. If the task is an accident investigation there is probably a different basis to rely on. The problem then could be that the identification of functions may rely too heavily on available descriptions of the accident (Hollnagel, 2012, p. 37). It may then be hard to distinguish the use of the FRAM from a conventional linear cause and effect-modelling tool. The balancing between unbiased descriptions of the functions and significance of non-linearity in the model is believed to be a dilemma.

7.3.2 Variability, functional resonance and instantiations

Variability of the functions, variability of the Outputs of the functions and the aggregation of variability, i.e. the functional resonance, were analysed in instantiations of the model. This was also when some of the potential couplings within the system were concretized into actual couplings. The strengths of the FRAM were manifested during the instantiations. The concepts of variability and functional resonance are easy to comprehend and facilitate the visualization of dependencies during the analysis. The variability of an Output was always described on an ordinal scale that referred to an anticipated Output from the function in question. This facilitated the transition to the function receiving the varying Output as an input, i.e. the downstream function. It may seem trivial but tells a lot about how a function's performance variability may propagate within a system and induce functional resonance.

Perrow's notions of complex interactions and coupling can be translated into the FRAM's notion of actual couplings. The actual couplings in an instantiation of the FRAM model show both connections that were not foreseen and the level of dependency, i.e. if the coupling is tight or loose. A function that is affected by a varying Output from an upstream function may vary differently depending on which upstream function that is involved. The function may also react differently depending on which aspect that is receiving the varying input. These two properties demonstrate the level of coupling between to functions. Hence Perrow's notions are clearly present when the FRAM is applied for analysis.

There is one cautionary reflection to account for even though the instantiations were comprehensible tasks to perform. When the actual couplings are analysed, it is easy to get carried away and see an awful lot of couplings everywhere. For the analysis to be valuable and consistent it is assumed that a critical perspective should be adopted during the instantiations. This leads to another important reflection, namely that a lone analyst should not conduct a FRAM analysis. Since the FRAM is overall qualitative it is assumed that discussions involving several competent individuals are the most efficient and thorough way of conducting the analysis.

7.4 Validation of the FRAM model and focus group discussion

A visit to the DNV headquarter outside Oslo was made as part of the process of this thesis. The combined experience within offshore safety is large at DNV and it is valuable to be able to involve a perspective from reality in the thesis. The intention was to discuss the reasoning in this thesis and validate the identified functions during a meeting with experienced professionals. As it turned out, there is a process at DNV that involves the search for suitable methods to apply when analysing dependencies. The actuality of the issue at the company rendered rewarding discussions.

The idea was basically to match the theoretical modelling of a system on an offshore platform with actual experience too see if it was principally correct. The idea was also to contrast between a theoretical perspective and a professional perspective, it was a bit of a surprise that our views conformed quite well. The inventory of identified functions related to fire fighting were validated during the discussions. Hence the FRAM model turned out to be principally correct in spite of the difficulties that were experienced during the identification. In addition to that, there was an agreement on the need to reflect on the limitations. This was in line with the previous discussion on the coupling between the identification and the system boundaries.

However, a few topics emerged as particularly interesting during the discussions. Some of these may be suitable for future research and they are accounted for in the upcoming section.

7.5 Future research

Suggestions to future research emerged both during the thesis work and during the discussions at DNV. The ideas will be accounted for briefly in this section.

- The coupling between the identification of functions and the system boundaries need to be explored. Is it, for instance, possible to attempt to create a common conceptual framework regarding the identification of functions and the required level of detail in the descriptions? How should limitations and the connections to the system boundary be handled in an optimal manner?

- Is it possible to incorporate a grading of the criticality of the functions in the analysis? Functions experiencing similar variability and having similar couplings can be of different significance to the system as a whole. It is probably a demanding rating to perform, experience and knowledge of the actual design of a system is assumed to be essential. May provide guidance on prioritizing between functions and may have large practical impact.

- How does functions with reduced capacity affect the conditions for the analysis? All functions are probably not delivering as intended all the time. Also, how do actions taken during a deviancy to get back to normal affect the variability and functional resonance?

- The consequences of the analysis will in one way form an input to the functions. How can this be accounted for? Actions taken due to results of the analysis will be a game change for the system. It is assumed throughout in this thesis that the system is complex, which implies that there is continuous adaption and several mutual processes within the system.

- How does the petroleum exploration in more extreme environments affect the variability of functions? Will an installation in e.g. the Arctic require more performance variability due to demanding environments?

8 Conclusion

The first question concerned the need to approach interdependencies in barrier systems. The safety management strategies within the industry have been developed in the spirit of the Swiss cheese model. It is a complex linear accident model that involves the use of barriers to strengthen safety. This kind of accident model is also denoted as an epidemiological model. It was concluded that models of this kind are incapable to provide tools for interpretation of dependencies within a system. The governing philosophy is therefore not considered sufficient when risk is perceived to be a product of complex interactions. Hence there is a need to approach the issue of interdependencies in barrier systems. Assessment of interdependencies should be incorporated in the system design phase. The incorporation is assumed to reduce the frequency of unanticipated interactions. With regard to this, the PSA prioritizes a matter that is important to the performance of barrier systems. It is though noteworthy that the impacts of complex interactions have been discussed for approximately thirty years.

The second research question concerned the required characteristics of a method to apply when the task is to interpret dependencies. This question was satisfactory answered during the literature studies, the method should:

- Apply a holistic perspective and account for non-linearity
- See risk as an emerging feature that is a product of complexity

The third question concerned the impressions from the application of a method that conforms to those the requirements. The application of the FRAM showed that it still has some development to undergo. The reflections from the application are of dual nature. On one hand the structure and purpose of the method is easy to understand. The FRAM does on the other hand not adequately address issues that arise since the system to be modelled is complex. That is because the construction of the FRAM model via the identification of functions is very uncertain.

The overall impression from the application of the FRAM is that it is an interesting and promising method. The concepts of variability and functional resonance are comprehensible for anyone, which indeed is good and makes the method more accessible. It is also possible to see the connections to Perrow's complex interactions and couplings during the instantiations of the FRAM model. It is though important that the FRAM model is reliable since it constitutes the preconditions for the analysis of variability and functional resonance. The construction of the model and hence the boundaries of the system via the identification of functions should be subject to continued development.

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