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An extended FRAM method to check the adequacy of safety barriers and to assess the safety of a socio-technical system

Sharmin Sultana [a,b,*], Stein Haugen [a]

[a] Department of Marine Technology, Norwegian University of Science & Technology, Norway
[b] Department of Research and Innovation, DynSoL AS, Norway

ABSTRACT

Safety barriers are used in the system to prevent unwanted events and accidents. Traditional approaches like fault tree or bow-tie method use linear accident models without considering complex interactions of failures of safety barriers. The present paper presents an extended FRAM model to identify required safety barriers and proposes a safety analysis method to predict the system's safety. The initial step of the method is to identify the necessary main and auxiliary functions to achieve the system goal. The later step is to determine the necessary safety functions to execute the main functions to achieve the system goal and to resist variability in performing the main and related auxiliary functions. A simple mathematical model is proposed to assess system safety based on the performance of existing barriers. The method is described with the help of a case study, the LNG ship-to-ship transfer process. The paper compares the extended FRAM method with other methods such as Bow-tie, FRAM-STPA, and Bayesian network. Analysis shows that FRAM can qualitatively, quantitatively, and dynamically assess system safety. The most vital point of FRAM lies in its capability of effective qualitative evaluation, which considers coupling between functions and related aspects, can be presented graphically, and future actions can be taken accordingly.

1. Introduction

Safety barrier management is crucial in reducing or maintaining control of a facility's process and system risk (Johansen and Rausand, 2015). Hardware (e.g., relief valves) or human (e.g., permission procedures), or a combination of both (e.g., manually actuated ESD system), can be used to create barriers. According to Petroleum Safety Authority Norway (PSA), the goal of barrier management is to develop and maintain barriers to the existing risk that can be managed by preventing or limiting the consequences of an unwanted incident (PSA, 2013).

Accidents are not single failures but rather complex situations of deviation of performance of several entities (Leveson, 2004). An increase in the dynamic complexity of the socio-technical system has made safety situations complicated. Accident scenarios for the presently used systems have become more challenging to describe. Examining potential scenarios and ways the system may behave rigorously is vital, ensuring that accident scenarios can be controlled and describing the scenario as realistically as possible. It is necessary to know the details of the accident's causes.

Most accidents in recent years are outcomes or the interaction of multiple aspects (e.g., technical, human, or organizational) present in socio-technical systems (Sawaragi, 2020). Traditional safety engineering approaches such as fault tree analysis, event tree analysis, failure mode and effect analysis cannot explain how multiple causes can lead to an accident (Thomas IV, 2013). Various system-based hazard analysis techniques have been developed to identify safety requirements in detail for complex socio-technical systems for solving the issue. Based on system-based accident modeling, proactive risk management strategies are developed, and the system is modified to prevent an accident (Rasmussen and Suedung, 2000).

In the conventional barrier approach, barrier performance is assumed constant, and risks are measured based on the static value (Zuijderduijn, 2000). In the ARAMIS (accidental risk assessment methodology for industries) EU project, coordinated by INERIS (French national institute for industrial environment and risks), bow-ties diagrams are used to identify significant accidents and check the sufficient safety functions. Each barrier's performance is evaluated based on response time, efficiency, and confidence level (Dianous and Fievez, 2006). The limitation of the bow-tie model is that it assumes accidents as a linear chain of events, which is not applicable when multiple causes are linked in complex ways. Another limitation of bow-ties is that barriers are not presented in a time or process following manner (Aust and Pons, 2020). Several works have been executed to overcome the limitation of the bow-tie. One such work is the work of Khakzad et al. (2013). They mapped the bow-tie model into the Bayesian network.

In the work of Bensaci et al. (2020), bow-tie and STPA (System Theoric Process Analysis) are applied together for detailed hazard

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* Corresponding author.

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identification and evaluation of risk scenarios. STPA is based on the STAMP (System Theoric Accident Model and Processes) accident model for dealing safety in complex socio-technical systems (Leveson, 2011). In STAMP, the system is decomposed into components into controllers and controller targets. STAMP contains input, output function, control, and human and functional behavior. Pre-condition, resources, and time elements are absent in STAMP (Qiao et al., 2019). STPA establishes a control structure and identifies potential unsafe control actions and their causes. It can extract various hazardous events caused by system interactions. The analysis is suitable for the automated system due to its control structures. It is a purely qualitative method.

The barrier performance degradation rate is dynamic and needs continual monitoring and processing of real-time data (Paltrinieri et al., 2015). Dynamic barrier management (DBM) infers barrier status in near real-time and evaluates the impact on risk level. However, the DBM framework is challenging to implement and requires further development to clarify steps. In the work of Hosseinniaa et al. (2019), the authors propose a three-phase process for the DBM framework: screening, re-evaluation, and implementation. During the screening phase, a design baseline is established for barrier performance monitoring and to know the effect on risk level, then tracking the changes affecting the validity of the baseline profile. This step can be further divided into a context model, categorization of system changes, and gap analysis. Several steps are followed, such as a risk barometer to establish the context model. Three significant changes include the change in context, knowledge, and conditions. The effects of identified changes are reviewed by performing gap analysis on barrier elements, barrier function, and system performance and assessing the impact on risk level.

FRAM is used to derive potential accident scenarios. It focuses more on the understanding of interactions in complex socio-technical systems. FRAM evaluates the concept of stochastic resonance. It can be applied by identifying functions with detailed information about how something is done, characterizing the variability of the functions, interpreting possible couplings, and providing suggestions to manage the unexpected variability (Tian et al., 2016). FRAM has been widely applied in various fields, such as healthcare (Patriarca et al., 2018), aviation (Herrera et al., 2010, Rutkowska and Krzyżanowski, 2018, Tian and Caponecchia, 2020), maritime (Lee and Chung, 2018, Lee et al., 2020, Qiao et al., 2022, Salihoglu and Beşikçi, 2021), railway (Belmonte et al., 2011, Yue et al., 2020), environment and process industry.

In the work of Huang et al. (2019), the author used FRAM in the railway transportation system. FRAM provides an understanding of interactions and emergence phenomena in complex socio-technical systems. It focuses on behavioral changes rather than human failures, which helps managers comprehensively understand security. In the failure caused by functional resonance, when the output of the function changes, the reasons for the changes can be analyzed and found, and the most effective improvement suggestions according to the resonance situation can be obtained. FRAM shows that accidents can be prevented by controlling the output of functions or adding barrier measures to functions, which focuses more on reducing unsafe disposable behavior. According to the authors, FRAM is a better method to reduce the probability of accidents effectively and quickly in a short period.

In the work of Rutkowska and Krzyżanowski (2018), the FRAM method is used to examine air traffic control (ATC) service, a complex socio-technical system, to determine complex interactions in the daily operation of the system. It is seen that the FRAM model can facilitate the monitoring and controlling of the variable performance of ATC work. It also describes how the system components' functions can resonate and create hazards due to, for example, the lack of data updates, which, if undetected in time, can lead to accidents or serious incidents. The model can analyze the workflow and provide the means to conduct risk analysis and prevent risk by corrective activities. Based on the created model, it is possible to take further steps. It would allow for a more detailed model expansion to supplement the ATC services' coordination and control transfer processes. The created model for coordinating and transferring control over aircraft may be utilized to confirm or refine the ATC services' operational instructions and perform their revision. Gad et al. (2022) apply FRAM to identify financial risk factors concerning relevant stakeholders before the construction phase. The work proved the applicability of FRAM in performing financial risk analysis to support the project management team during the construction project phases.

Anvarifar et al. (2017) applied a customized FRAM method to compare various design alternatives for multifunctional flood defense. While the customized FRAM approach has only been applied to a single specific scenario and system problem in this research, the proposed method seems promising for identifying the threats and opportunities associated with the design alternatives of multifunctional flood defenses during the conceptual design phase. The method provides a qualitative tool for a broader view, analysis, and visualization of many imaginable internal and external changes to the system, including various types of human, technical, and environmental interactions. Furthermore, it provides a unified terminology and convenient framework to be used by the developers of multifunctional flood defenses from different domains. Additionally, the results can be used to identify the possibilities for appropriately increasing the system's flexibility to respond to various human and environmentally induced unexpected events. Overall, FRAM can serve as a valuable complement to the reliability analysis methods for enriching the risk analysis of multifunctional flood defenses. The proposed method, however, suffers limitations and needs further development. Guidelines are required for developing the scenarios and how much detail to include in the analysis.

Vieira and Saurin (2018) applied FRAM for a case of an environmental disaster that occurred in Brazil. FRAM made it possible to derive the system's outputs encountered in the disaster moment along with the magnitude of these outputs in each function. Actions are proposed to prevent similar disasters, and a discussion regarding the utility of this method in socio-ecological systems is presented. In the work of Seo et al. (2021), the authors applied three methods, AcciMap, STAMP, and FRAM, to analyze a fire accident. Although the approaches to finding the cause of an accident in these three methods are different, the results are almost similar. AcciMap and STAMP models are hierarchical. They play complementary roles in analyzing each component of the system. FRAM is more effective for analytics centered on human and organizational functions.

FRAM has been combined with other methods like STPA RAG to address industrial problems (De Linhares, 2021; Toda et al., 2018). FRAM combines accident causation analysis and a taxonomy model to identify and analyze operational risk (Li et al., 2019). FRAM can be used as a method to propose indicators where there is a high probability of performance variability. Sequentially timed events plotting method (STEP) and FRAM model are addressed in the work of Herrera and Woltjer (2010). STEP illustrates the event sequence showing the relationship between allocated authorities and the time sequence. One advantage of FRAM is that it helps the analyst look beyond the specific time sequence and failure under analysis. It provides a more comprehensive understanding and more effective learning of a possible accident (Herrera and Woltjer, 2010). It is possible to instantiate accident scenarios occurring in a limited time interval by FRAM.

Albery et al. (2016) executed a comparative risk assessment with various tools like work as imagined vs. work as done, risk matrix, and FRAM. The assessment showed that the comparative risk matrix focuses on specific hazards and their controls in isolation. The evaluation of work imagined vs. work as done also identifies local hazards and indicates hazard prevention. However, for a modern complex system to include variability in the overall structure and to gain comprehensive knowledge about the state of other related systems, a comprehensive tool is needed, which is possible by FRAM. FRAM assesses barrier management for offshore drilling in the work of Pezeshki (2020). Their case study demonstrates the method's potential barrier management in the strategy development phase. A potential hazard is identified first. Reactive barrier functions were integrated using the FRAM model.

Scenarios that can increase variability are controlled. The scenario analysis shows that variability is increased in human functionality and not the technical elements of the system. One great strength of FRAM is that it can be considered an iterative barrier strategy procedure in barrier management (Herrera et al., 2010).

Despite many recent works; only a few cover the quantitative evaluation of FRAM. A semi-quantitative FRAM is proposed by Patriarca et al. (2017) based on Monte Carlo simulation to assess performance variability in a complex system. The work summarizes various aspects like the complexity level of the system, organization condition, system condition, and disruption effect. In case of variability increases due to external conditions, functional resonance affects other functions, which makes other potential sources of variables. Human organizational factors such as communication coordination play an essential role in each function's execution. Yang (2020) proposed a formula consisting of safety entropy, functional conformability, and system complexity to check the spontaneity of the safety state-changing process.

Davatgar et al. (2020) use a mathematical model to visualize the link between changes in risk influencing factors and their effect on every part of the system. The Katz centrality algorithm assigns the initial edge weight of corresponding background functions. A dynamic FRAM graph model is presented for assessing operational risks arising from maintenance. The dynamic FRAM graph model systematically manages the couplings and functional variability information to lessen the effort needed to identify possible resonance propagations. RIFs related to functional variability are defined to evaluate the functional variability score in background and foreground functions to capture this concept. This approach captures the effect of changes within the system. It systematically prioritizes critical stages and interactions during maintenance work through graph topological analysis by considering Katz's centrality and Edge betweenness algorithms in two different operational situations.

An extended FRAM method is applied in the present paper to check the adequacy of safety barriers for a process system used in the chemical and petroleum industry, where technologies are well understood. Safety barriers refer to actions, procedures, resources, or equipment to keep the system in place or achieve the system's goal. In the case of these process systems, failure of barriers will create unwanted accidents and events. There can be many types of variability in other systems, e.g., geographical territory, financial organization, and public administration. These types of systems will require distinct types of measures to prevent system degradation. The method to find out system degradation relevant to those systems and measures to resist those degradations is not considered while developing the method and conducting the paper's case study. The method described in the paper is developed considering risk and safety barriers applicable to a chemical or petrochemical process system.

FRAM is adopted considering its potentiality to evaluate interactions of various factors in the system and dynamic behaviors suitable for the present socio-technical system. In previous works of FRAM, the hazard identification method is not well established, and a mathematical model for risk assessment is scarce. Further challenges exist regarding barriers, indicators, and re-design of functions and organizing data during the early stage of accident investigation (Herrera and Woltjer, 2010). Present work focuses on further study in this direction. FRAM method is extended to include a quantitative assessment tool to predict system status based on performance evaluation of existing barrier functions. The adequacy of barriers is also checked with the Bayesian network, FRAM-STPA, and Bow tie method. A qualitative comparison is made among them.

The case study chosen here (the LNG STS system) has already been studied in the academy and industry (Aneziris et al., 2021; Fan et al., 2022; Wu et al., 2021; De Andrade Melani et al., 2014). However, the reason for analysis again is that from the analysis of a known system, the effectiveness of the study's method will be visible. It will be clear whether the industry will be benefitted from the method, whether methods can improve the system's safety, and how companies will be helped. The paper is arranged as follows: In the first section, the necessity and background of the research are explained. The second section describes the analysis methods executed in the paper and their procedure. The third section shows the execution of the method with a case study. LNG (liquified natural gas) ship-to-ship transfer is chosen for the case study as it involves excellent interaction of humans, technology, and organization. The following section discusses the insight obtained from the analysis and concludes.

2. Method

The present extended FRAM method can be used for a system's hazard analysis or safety analysis. The method is implemented in several steps. The first four are related to functions and their execution for achieving the system's goal. Rest two are related to identifying required safety barriers that will ensure the implementation of main functions if they can be executed appropriately. As a result, the system's goal will be achieved precisely and timely.

2.1. Step 1:Identifying functions and aspects related to the goal of the system

The method's foremost step is to determine the system's goal precisely. For a chemical plant, the goal is to produce chemicals in a predetermined quantity on time in a safe manner. Related goals are to produce chemicals 'in predetermined quantity, 'on time', and 'safe execution'. The system's main function is identified based on the goal and understanding of how the system operates. Any distinction is not made for the type of entity performing the task (technical, human, or organizational) during identification. Description of function should provide necessary information to achieve the specified goal. Functions related directly to system goals are defined as 'main functions'. Additional functions are required for the execution of the main function. They are termed 'auxiliary functions'. In Fig. 1, F3 is the main function related to the system's goal. F1 and F2 are auxiliary functions, meaning the F3 function will be executed after F1 and F2. In other words, the F3 function cannot be performed without performing the F1 and F2 functions.

Next, aspects are defined related to each identified function. Five aspects are conceptualized similarly to typical FRAM (Patriarca et al., 2020). Output (O) results from the function related to a goal or related to the next target task. The final output function can be getting the desired product for a chemical process. Input (I) starts the function or preliminary task for the output function. Input for 'getting desired produce' can be 'inserting raw materials into the reactor'. Pre-condition (P) are conditions that must be fulfilled for executing the function. For example, the operator must be present during operation, or ambient conditions should fulfill the predefined criteria to start the function. Resources (R) are needed for carrying the function, for example, equipment, instruments, utility, procedure, or guidelines (Patriarca et al., 2020).

Control is anything that helps to monitor or control the function. It can be local operators carrying the task or supervisors or management monitoring it. Time (T) is the determinant related to the duration of the output function. It can be specified as a target, and functions can be set accordingly. For example, if 3 min target is set to finish the task, the time is 3 min. Other input functions and required pre-conditions can be set accordingly. If the task duration takes longer, the goal is not fulfilled (Patriarca et al., 2020).

2.2. Step 2: Determining interaction between functions

The interaction between functions, including aspects of each function, can be determined to visualize coupling between upstream and downstream functions (Erik, 2017). Description of each aspect of a function points to one or more other functions since the aspect of that function must be provided by the performance of those related functions. The FRAM diagram (Fig. 1) depicts the system's functions and interaction paths. Upstream is linked with downstream aspects like input, pre-condition, time, control, or resource. For example, both function 'F1′ and 'F2′ are downstream functions of F3. Resource of F3 is linked to the output of function' Resources arrives'. The pre-condition of function F3 is related to 'Task to meet PC'. Control of function F3 is related to the 'Control arrives' function. This coupling is determined by looking at the system as a whole, functions that should be performed to achieve the goal, characteristics of how integrated to achieve the goal, and how one element influences other functions or aspects.

2.3. Step 3: Identify variability in functions and aspects

This step determines what variability can happen in the function and aspects. Variability is determined by the potential abnormal performance of each function. Possible performance of a function falls into four categories: Precise, Omitted, Imprecise, Too late/stopped in the middle. Descriptions are as follows:

i) Precise: A function is performed as required in time and with expected precision
ii) Omitted: A required function is not performed at all
iii) Imprecise: A required function is performed insufficiently with unacceptable precision
iv) Too late/stopped in the middle: A required function is performed late or stopped in the middle

The variability of a function is highly related to other aspects (input, pre-condition, resources, and control) of the same function. Any variation in the performance of these aspects will affect the output function and, thereby, goal-related o it. The performance of the five aspects is mirrored in the performance of the upstream function. When the variability of multiple functions resonates, the outcome of upstream functions varies unexpectedly. The variability of a single function is usually inadequate alone to cause an accident. When the variability of several functions resonates, variability might exceed the standard limit and result in an incident (Hollnagel and Goteman, 2004). The variability of aspects and the possible effect on the output are described in Table 1. The insufficient output of function F3 can be caused by variability in its four aspects or F1 or F2 (Fig. 1).

2.4. Step 4: Identify resonance effects or causal factors of the variability

This step is to identify the root causes of the variability. Root causes of variability are related to other functions. Route cause is the resonance effect of variability of other downstream functions of a specified function (De Carvalho, 2011). Route cause is identified considering each type of variability. In Fig. 1, a variability of F3 can be that F3 is not executed. Causal factors can be input function (F1 or F2) not executed or Precondition does not meet as 'task to meet PC' not executed. Other causal factors can be the absence of resources or control. The execution time of function F3 will be late if the execution of function 'arrival of resource' is late or the implementation of function 'arrival of control 'is late (Fig. 1). In this way, a deterioration in function performance or variability in function performance is developed from the resonance effect of variability of other related functions or aspects.

2.5. Step 5: Establish required safety functions to prevent variability of functions and related aspects

This step determines the safety functions that need to be implemented in order to avoid variability of functions and their aspects. Safety functions are related to the safe execution of the main and auxiliary functions. Safety functions are determined by considering the variability's resonance effect or route cause. Each safety function represents a safety barrier. The system's safety deteriorates when related safety functions cannot be executed in time. Safety functions are allocated considering three conditions:

i) Safety function to nullify the reason for abnormal state of aspects which resonates from downstream functions and aspects
ii) Safety function to nullify the reason for the abnormal state due to external effects

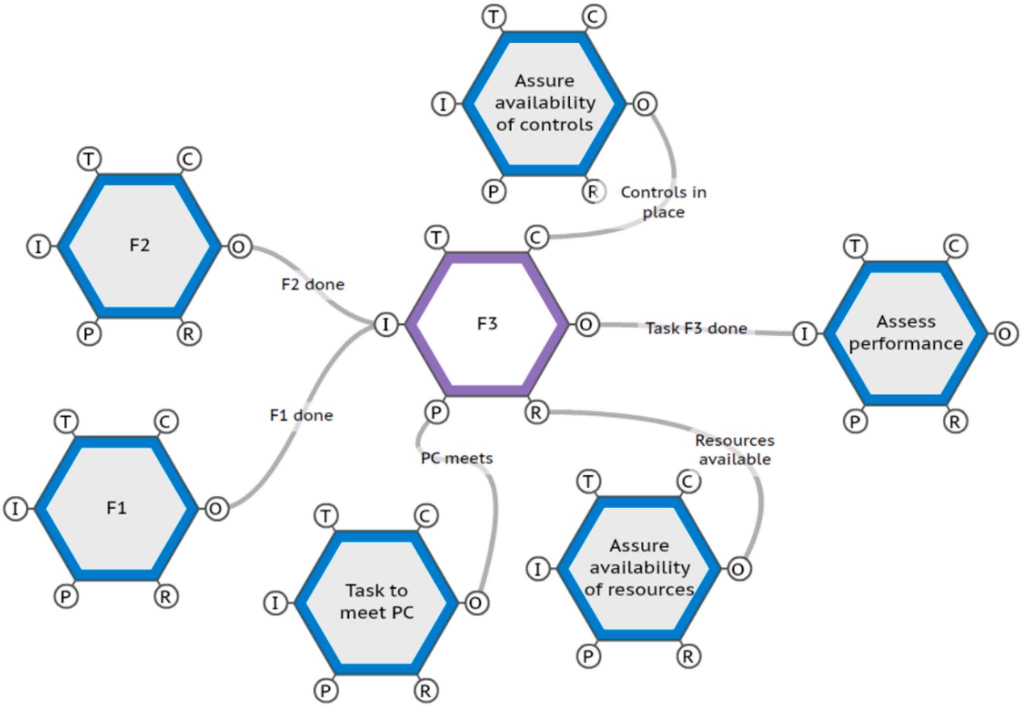

Fig. 1. Coupling between functions in FRAM.

Table 1
Variability of aspects and possible output variability.

Aspect	Variability of the aspect	Description	Possible output variability
Input	Omitted	Not executed at all	Not executed
	Imprecise	Executed with deficiency	Imprecise/Not executed
Pre-condition	Omitted	Pre-condition could not be met	Imprecise/not executed
	Imprecise	Pre-condition met with deficiency	Imprecise/not executed
	Late/stopped in the middle	Pre-condition met later	Later/not executed
Resource	Omitted	Resource is absent	Imprecise/not executed
	Imprecise	The resource is present with a deficiency	Later/imprecise/not executed
	Late/stopped in the middle	The resource is present later	Later/imprecise/not executed
Control	Omitted	Control is absent	Imprecise/not executed
	Imprecise	Control is present with deficiency	Imprecise/not executed
	Late/stopped in the middle	Control is present later	Later/imprecise/not executed
Time	Too short	Function execution took a longer time	imprecise
	Too late	Function execution took a longer time	Later
	Stopped in middle	Function interrupted in the middle	Later/imprecise/not executed

iii) Safety function for mitigation of the abnormal state that affects upstream functions

There can be various safety functions to prevent the variabilities. All possible functions should be considered to establish redundancy of safety. For example, there can be multiple safety functions like sf1 or sf2, or sf3 To execute function F3 precisely (Fig. 2). All should be considered here. After determining the safety function, each aspect related to the safety function is defined. Achievement of the goal depends on the state of output functions, which relies on the state of the input function, precondition, resources, control, and time. These states rely on the execution of safety functions. If one safety function cannot be executed, it will affect others. Safety functions should be managed properly to ensure the avoidance of hazards.

2.6. Step 6: Identify safety performance indicators

The result of FRAM analysis, obtained from step 5 of the method (Section 2.5), can be utilized to determine a system's performance indicator. Safety barrier performance indicators are determined by translating safety functions into quantifiable quantities. While translating, required input functions, resources, or controls related to safety functions are converted into measurable attributes used as indicators. These are leading indicators indicating potential safety actions taken by the facility. Lagging indicators can be developed using the system's variability of function and aspect. It indicates performance variability observed in the facility in a specified period. An example of translation is shown in Table 2.

2.7. Step 7: Assessment of safety performance of the system

The system consists of multiple levels. The performance of a target function depends on the contribution of various aspects from different levels. This level distinction is based on the execution sequence, not on time. Because functions at the various levels need to be executed simultaneously, it depends on the necessity of the system in Fig. 2, F3 is the main target function that is directly related to the goal. Resources R, Control C, Pre-condition PC, and Input function I are connected to this function at level i. Each aspect is related to other required functions at level i-1. Each function at i-1 is related to some other functions at level i-2.

Two factors assess the system's safety performance: aspect weight

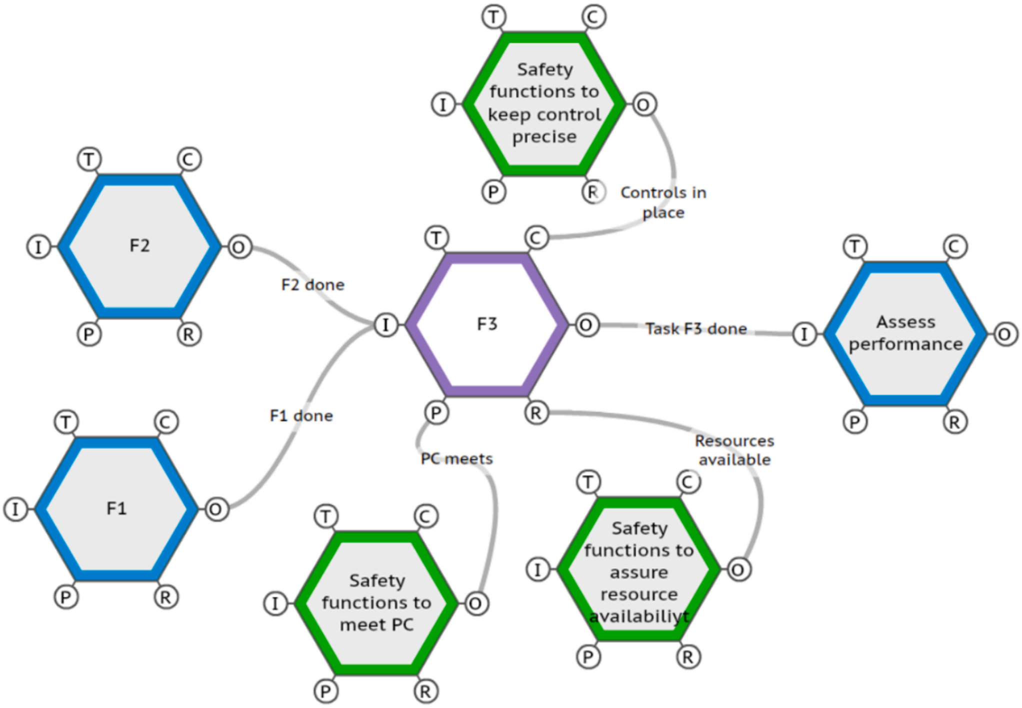

Fig. 2. Safety function for executing a target function in FRAM.

Table 2
Development of performance indicators from aspects of safety functions in FRAM.

Safety function	Related aspects	Related functions/ attributes	Performance indicators
Safety function S1	Output function OS1		
	Input function IS1	Actions are taken starting IS1	The number of the actions taken starts with IS1, quality of actions
	Pre-condition PCS1	Actions were taken to fulfill PCS1	Number of actions taken to fulfill PCS1, quality of actions
	Control CS1	Actions were taken to maintain control of CS1	Number of actions taken to maintain control of CS1, quality of actions
	Resources RS1	Actions were taken to assure resource availability RS1	Number of actions taken to assure resource availability RS1, quality of actions
Safety function S2	Output function OS1		
	Input function IS2	Actions are taken to start IS2	Number of actions taken start IS2, quality of actions
	Pre-condition PCS2	Actions were taken to fulfill PCS2	Number of actions taken to fulfill PCS2, quality of actions
	Control CS2	Actions were taken to maintain control of CS2	Number of actions taken to maintain control of CS2, quality of actions
	Resources RS2	Actions were taken to assure resource availability RS2	Number of actions taken to assure resource availability RS2, quality of actions

and deviation. Weight is assigned to three ranks.

- High weight (Rank is 3): if the function is related directly to the main function, the variability of this aspect affects the main function or goal directly. In Fig. 3, aspects located at level i will have a high weight, so the rank is 3
- Moderate weight (Rank is 2): if the function is not related directly to the main function, but instead to an auxiliary function, the variability of this aspect will affect the main output function or goal moderately or little. In Fig. 3, aspects located at level i-1 will have a moderate weight, so the rank is 2
- Low weight (Rank is 1): if the function is not related directly to the main or auxiliary function, related to a safety function with enough redundant safety functions. So, the variability of this aspect will affect the main output function or goal minimally. In Fig. 3, aspects located at level i-2 will have a low weight, so the rank is 1.

The variability score is determined based on the present performance of functions and aspects and their ideal state. Present performance can be determined by monitoring performance indicators at the previous state. If each aspect is in its ideal situation, variability will be zero. The critical point is to determine the ideal situation. The ideal situation can be assumed as industry best practice. The output will be precise in quality and time if variability is zero. A zero to four variability score table can be created to find the overall output score. Four is the maximum variability state. A maximum variability of 4 means no output from the output function, resources are absent entirely, pre-conditions are not met, or controls are not present.

The following equation is utilized to determine the safety performance of the system:

$$SC_{p,i} = \sum_{j=1}^{m}\left(\left(W_{i,j}{}^{*}\Delta V_{i,j}\right) + \left(W_{R,j}{}^{*}\Delta V_{R,j}\right) + \left(W_{PC,j}{}^{*}\Delta V_{PC,j}\right) + \left(W_{C,j}{}^{*}\Delta V_{C,j}\right)\right) \tag{1}$$

$$\Delta V_i = \sum_{df=1}^{n}\left(\left(w_o{}^{*}\Delta v_o\right) + \left(w_R{}^{*}\Delta v_R\right) + \left(w_{PC}{}^{*}\Delta v_{PC}\right) + \left(w_C{}^{*}\Delta v_C\right)\right) \tag{2}$$

In Eq. (1), $SC_{p,i}$ represents the prediction of the variability of a specific function at a specific time at level i, $W_{i,j}$ Represents the weight of input of jth function of level i. $\Delta V_{i,j}$ represent variability score of input of jth function at time t, $W_{R,j}$ represents the weight of resources of j^{th} function, $\Delta V_{R,j}$ represent variability score of resources of jth function at time t, $W_{PC,j}$ represents the weight of pre-condition of jth function, $\Delta V_{PC,j}$ represent variability score of pre-condition jth function at time t, $W_{C,j}$ represents the weight of control of jth function, $\Delta V_{C,j}$ represents the weight of control of jth function at time t, m is the total number of related safety functions.

In Eq. (2), ΔV_i depends on output function, resources, pre-condition, and controls of its related downstream function df_1 at level i-1. w_o is the weight of the output function of downstream function df_1. Δv_o is variability in precision or time of that output function df_1. w_R is the weight of resource of function $df_{1.}$ Δv_R is variability in the performance of resources. w_{PC} is the weight of the pre-condition of function df_1.Δv_{PC} is variability in the performance of the pre-condition. w_C is the weight of control of function $df_{1.}$ Δv_C is the variability of performance of control of function df_1. N is the total number of downstream functions. Similarly, variable downstream functions related to resources, pre-condition, and controls are determined using equation (ii).

3. Case study

STS transfer of LNG is carried out in port. After arrival and mooring of an LNG cargo ship, required tasks include inserting the LNG transfer line, checking storage tank systems and related equipment, earthing, connecting hoses & links, opening the manual and automatic valves, and, finally, starting the pump. After completing the liquid transfer, operators stop the pump, purge the lines, and disconnect the hoses. It is essential to follow the sequence to ensure the safe and proper execution of the transfer. The main component of the STS transfer process is the pump. Other vital components include control valves, motors, hoses, and pipelines. During operation, flexible pipes from the storage tank of the carrier ship are connected to the storage tanks of the storage ship by manifold. Valves are used to control or regulate liquid flow, and thermal relief valves are installed with pipes to control the temperature or pressure of the fluid. The electrical system provides energy to operate the motor driving the pump. An adequate amount of power must be available for the actuators to perform the commands. Modern process systems are equipped with logic controllers or programmable controllers, by which all the components, like pumps and valves, can be controlled. Control room operators can observe all plant operations to ensure everything works correctly. Fig. 4 presents a simplified process flow diagram. Both ship authorities can monitor the transfer conditions, e.g., system pressure, tank volume, and equipment behavior.

3.1. *Identify system functions and aspects related to the main goal*

The first task is to identify the system goal for which the system is operated. For the present system, the main goal is the transfer of LNG from the carrier ship to the receiver storage tank precisely and on time, maintaining all safety protocols. The main important function related to the goal is the delivery of LNG. There are several other upstream and downstream functions related to this main function. Downstream functions are opening the valve, connecting hoses, and earthing, checking the storage tank, and the arrival of the storage tank. Upstream functions related to the execution of the main function are to stop the pump, purge the line, and disconnect the hose. Aspects pertaining to main functions are also identified. For LNG transfer execution, the output function is delivery complete. The input function is the start of LNG supply at the inlet pipe. Pre-conditions are pre-operational tasks

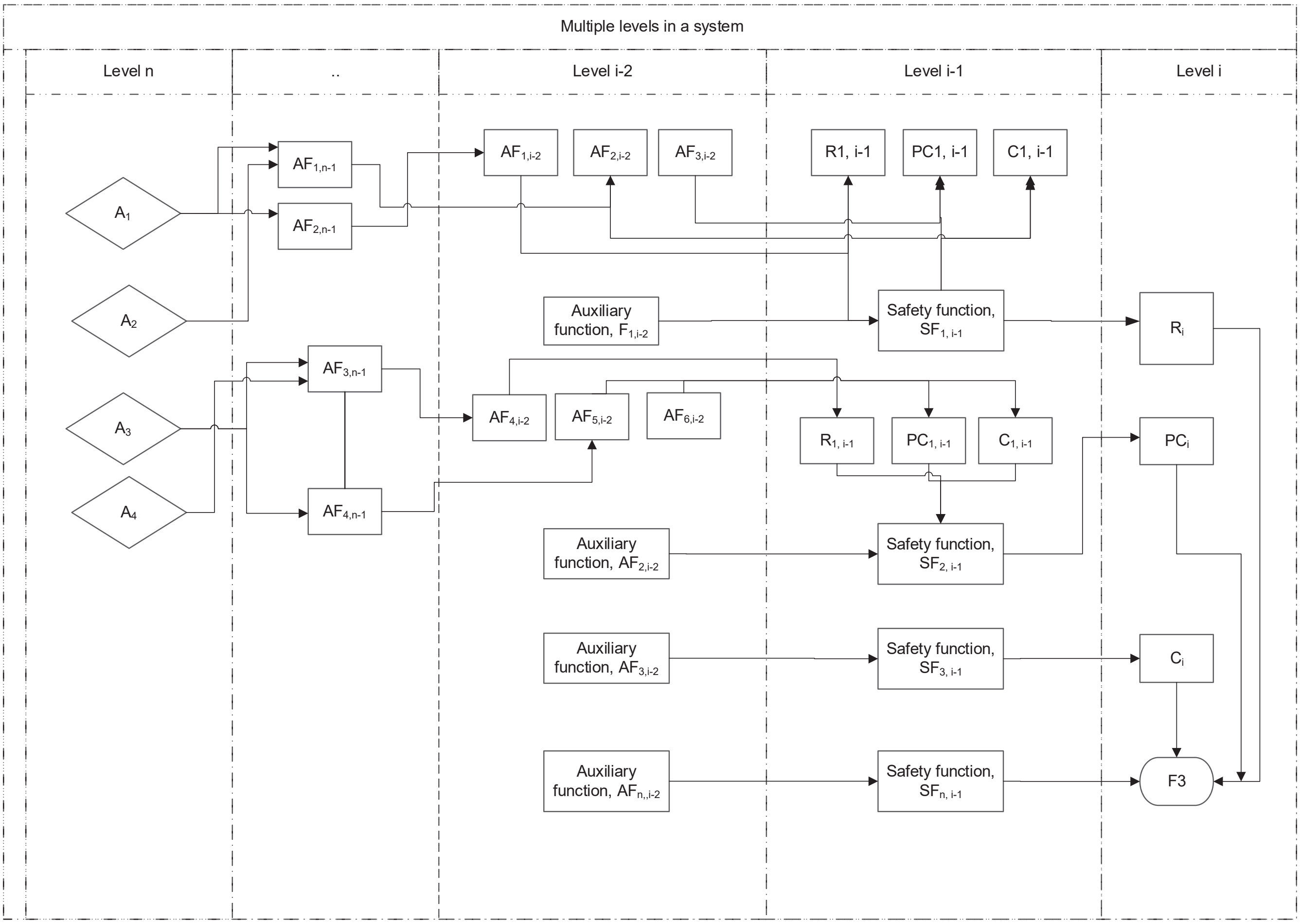

Fig. 3. Contribution of function from multiple levels to the end target function, F3.

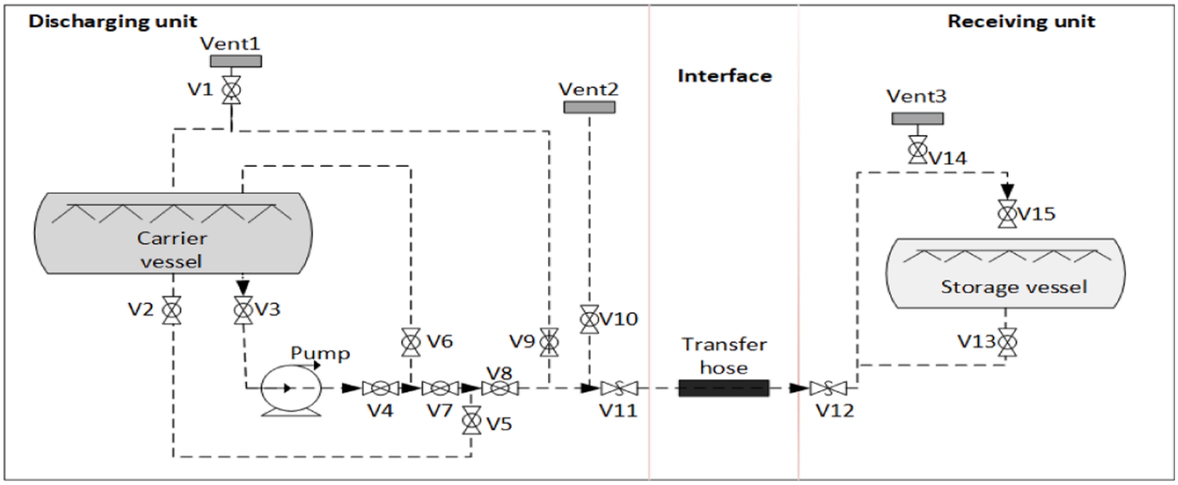

Fig. 4. Process sketch of LNG ship-to-ship transfer procedure.

completed: purging, opening valves, connecting hoses, and checking storage tanks. Resources are all related to equipment, instruments, utility, and procedures. Related equipment is the storage tank, pipe network, pump, and cooling system (Fig. 4). Instruments are thermal relief valves, flow control valves, vent valves, high-level alarms, telecommunications systems, and programmable logic controllers (PLC). Utilities are electricity telecommunications systems. Controls are local operators, PLC, supervisors, plant management, and port authority.

3.2. *Determine interactions between functions*

Interconnections are shown in the diagram (Fig. 5). If all the aspects are present, e.g., all resources are present, pre-conditions are precise, and controls are functioning precisely, it is expected that functions will be executed precisely and on time, so the goal will be achieved. If any aspect or element of an aspect is missing, it will affect the output function.

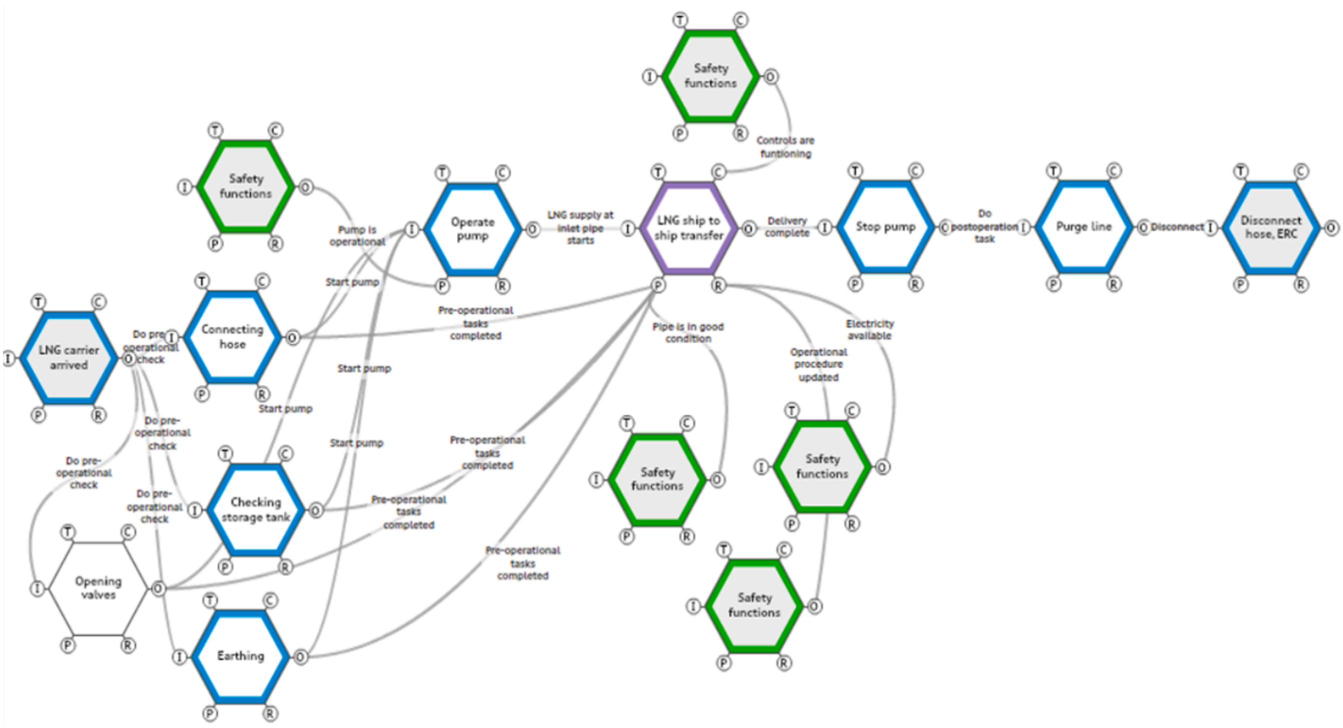

Fig. 5. Steps in LNG ship-to-ship delivery.

3.3. *Identify variability in functions and aspects*

For LNG ship-to-ship transfer, variabilities are first identified for the main function. For the main function of LNG ship-to-ship transfer, three types of variabilities are: LNG is not delivered at all, LNG could not be delivered in a storage tank in expected quality, and LNG delivery took longer than the target. Variability of aspects of the functions is also identified. The variability of the input function is that pump could not be started. Pre-conditions are varied because pre-operational tasks were not completed, e.g., checking LNG storage tanks, earthing, proper connection of hoses, or opening valves. Variability in resources can be that electricity is not available. Other variabilities in controls can be that valves are blocked or do not work, problems in telecommunication systems, and PLC is not working correctly. Variabilities in control can be the absence of a local operator or plant supervision.

3.4. *Identity resonance and causal factors of variability*

The causal factors for each variability are identified. For imprecise or deficient LNG delivery, causal factors or variability downstream can be LNG phase changed during transfer or bad LNG quality from the ship. For storage tanks, high-level downstream variability can be related to control and resources. Upstream variability can be a fluid loss. Causal factors evaluated from downstream functions or aspects are identified for each function and aspect. In the same way, the resonance effect in the upstream functions is also specified.

3.5. *Identify required safety functions to prevent variability and mitigate variability*

Safety functions are identified to prevent variability of the main function. Related aspects of these safety functions are also identified. For variability, LNG is bad quality; a safety function is to adopt a quality check procedure. The input function of this function is to assign personnel for the quality check procedure. Resources can be local operators and quality check procedures. Controls of these functions are plant supervisors. As said earlier, for precise LNG ship-to-ship transfer, all resources and controls should be made available, and pre-conditions should be met before the occurrence of the function. One resource is pipe networks. These are safety barriers as defined traditionally. Several safety functions can be executed to ensure the target function ’keep the pipe network in good condition. If one of the required safety functions is not implemented, still pipe network can work or can deliver its intended function. However, if all safety functions are missing, the pipe network will likely not serve precisely. Various essential safety functions can be pipe check before the operation, regular inspection and maintenance, condition monitoring after a specified period, and pipe insulation to keep the pipe network in good condition. Some downstream functions should be executed to execute these safety functions, e.g., assigning personnel for pipe check, inspection, and maintenance, developing a procedure for inspection and maintenance, and following existing standards. All possible downstream functions should be determined to go into the root cause of a function or aspect variability and keep adequate safety barriers in the system. There can be another scenario also. A pipe network may become deficient for inappropriate downstream safety functions or other external effects. The facility should take action to resist both downstream and upstream resonances.

First, the variability of a function or aspect of a function is defined to find the mitigation barriers of a potential mishap. Then a target function is defined to mitigate the variability. Here, the focus is on mitigative rather than preventive safety functions. A Variability of the pipe network is pipe defect. The related target function is ’to bring pipe network in good condition. Related auxiliary functions are ’to repair’, ’mitigate defect’, and ’to mitigate further risk’. Related required preventive safety functions are identified and presented in Fig. 6. Mitigative safety functions related to ’bring pipe in good condition ’are identified and presented in Fig. 7.

3.6. *Development of safety performance indicators*

The result of FRAM analysis, obtained from step 5 of the method (Section 3.5), is utilized to determine the system’s performance indicator. The required safety function ’keep pipe network in good condition’ (Fig. 6) is translated into measurable quantities, which vary in

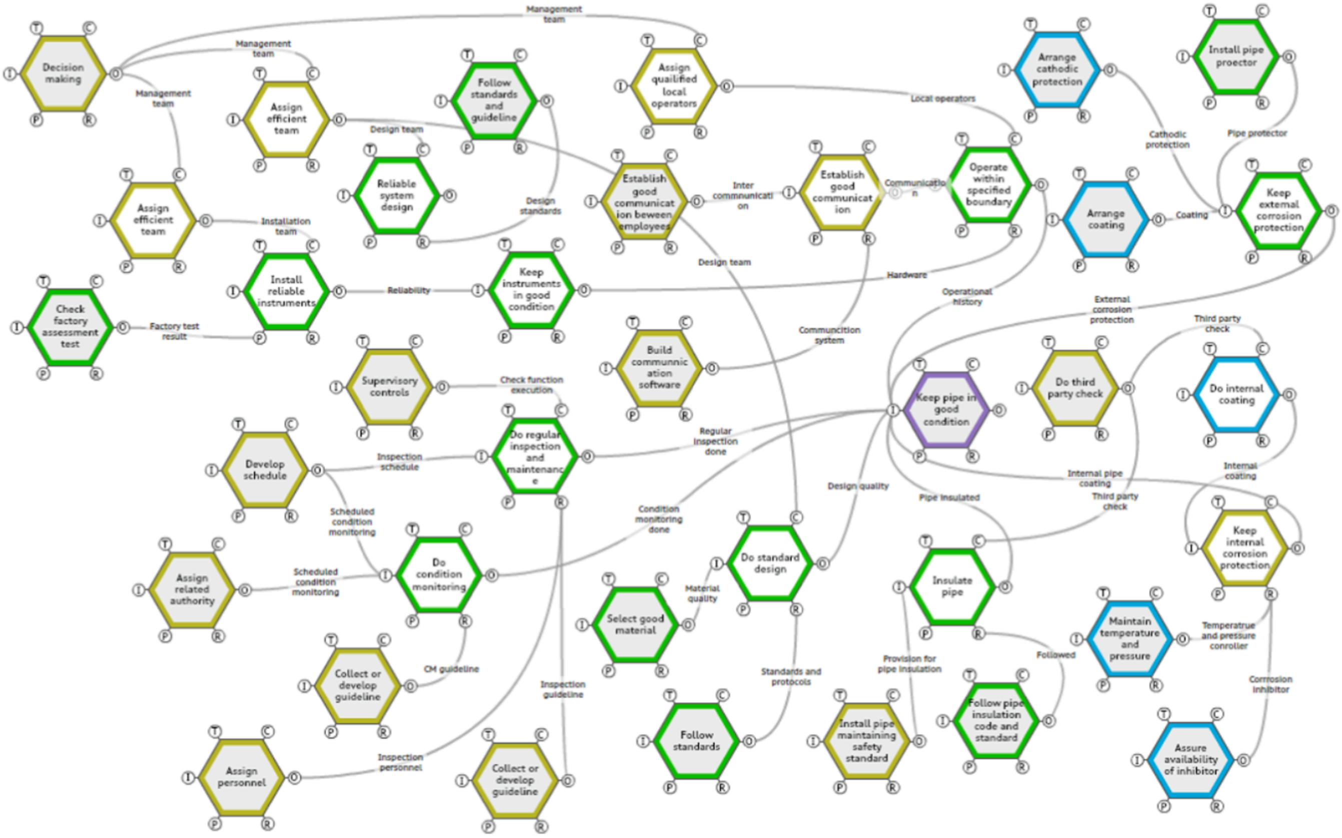

Fig. 6. Required safety functions to keep pipe network in good condition.

duration, frequency, or competency. For the safety function 'keep pipe network in good condition', leading indicators are frequency of condition monitoring of the system, the competence of people for condition monitoring, frequency of maintenance of system, and the competence of people for maintenance. Related performance indicators are developed considering the required downstream functions of 'keep pipe network in good condition. Fifteen indicators are found, which are leading indicators that prevent the event from occurring. Variability functions are used to develop lagging indicators (Table 3).

3.7. Assessment of safety performance of the system

A two-level mathematical model is constructed to determine the safety performance of the LNG STS system; in the present case, two levels will be enough to understand the required functional performance and variability. The safety assessment model is constructed for only a part of the system. The mathematical model includes two required safety functions, ' condition monitoring of pipe network' and 'regular inspection and maintenance due to the limitation of the scope of the present paper. Function execution of pipe checks before operation depends on efficient personnel allocation, procedure development, a balanced workload, and a good work environment. Various subfunctions related to the safety function are given different importance scores considering their importance for executing the function. The final part of the mathematical model is to revise the variability score considering the inter-dependency of the functions and related aspects. The overall score is determined after the revision of the scores (Table 4).

4. Discussion

An extended FRAM method is applied in the paper to check the adequacy of safety barriers and safety assessment of the system. LNG STS system is chosen for the case study. In FRAM, the system is decomposed into system functions. Each function considers input, output, time, control, pre-condition, and resources. Functional relationships can represent human, hardware, and organizational behavior and their relationship. Variability in function is described as output timing and precision. The model shows each element's contribution to a function's outcome. Each aspect has a different perspective and contribution to the execution of a function. While using FRAM for barrier identification gives an idea of how to increase safety measures for executing a function and other relevant requirements.

The analysis in the case study shows how an accident can develop from complex interactions of various imprecise performances. The significant insight from the research is that one minor issue can often significantly impact the system's performance in actual cases. If that minor issue can adequately be handled (Weick and Sutcliffe, 2001), avoiding accidents will increase. In the traditional risk analysis model, often, these issues are neglected due to low probability. Research indicates that even a low probability event can significantly impact the system. The probability and severity of unwanted events will be considerably higher if several significant issues merge into a socio-technical system.

Variability of a function resonances with the variability of other functions or propagates among functions so that the system can deviate much from the acceptable limit. Every entity, including humans, machines, and organizations, plays a vital role in a socio-technical system. The function of each entity, even a single sensor, carries importance from a safety and economic perspective. Each controller's required time constraint, resource availability, and pre-condition fulfillment can be visualized from dynamic analysis. From the gained observation company can act in all possible ways. Confusion arises in assigning duties at the right time and to the proper authority. Function-wise analysis like FRAM can consider both time constraints and authority allocations. It considers both control and time requirements for each function. Redundant barriers are always emphasized in a highly hazardous

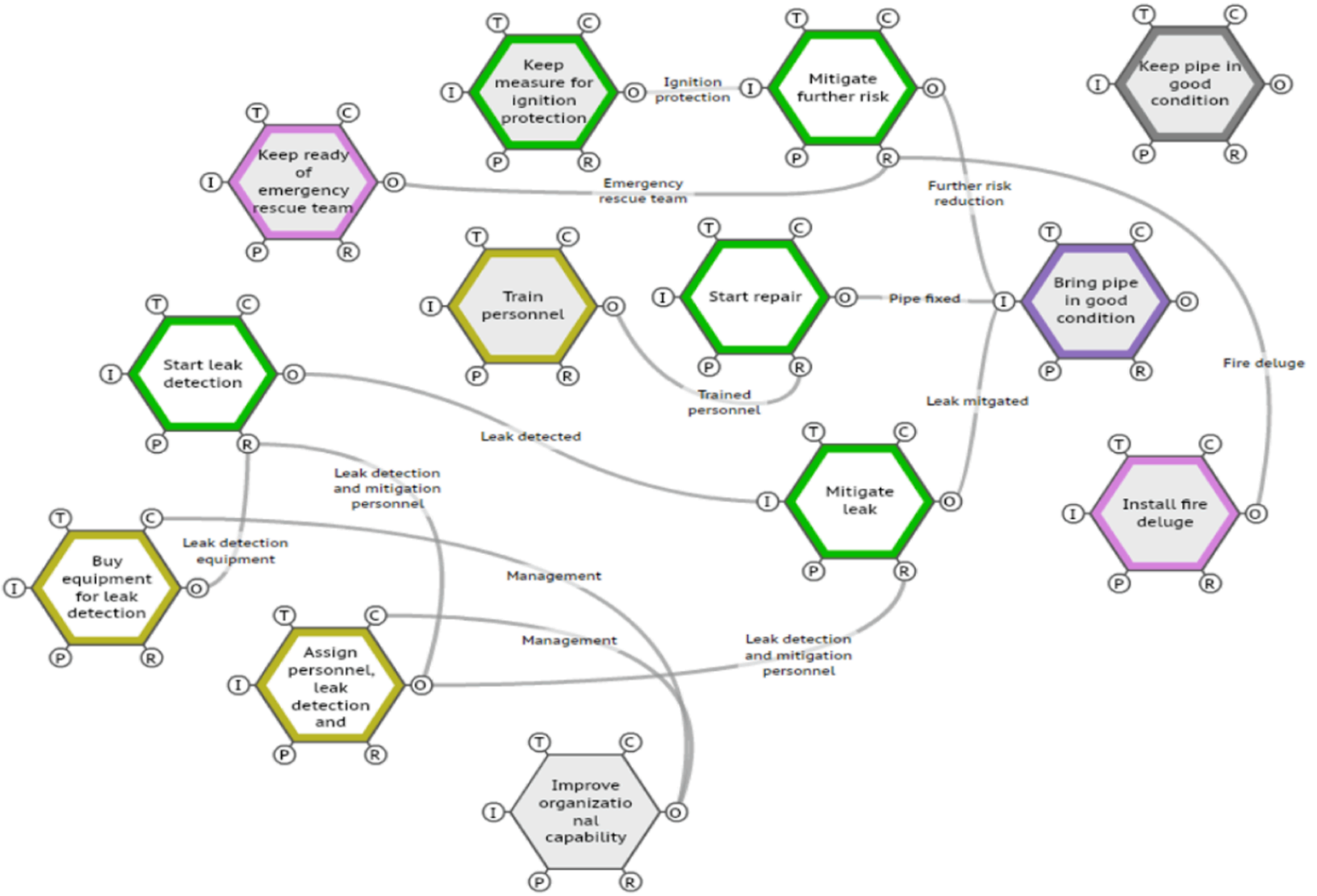

Fig. 7. Required safety functions to mitigate the variability of pipe defect or 'bring pipe network in functional state'.

industry. So even if one barrier fails, the system can still sustain, and production can continue. FRAM analysis can be helpful in consideration of redundant barriers. Variability and resonance can be considered by considering the absence of the required safety function, and alternatives can be sought to execute the main functions and achieve the final goal.

If small missing functions can be identified and mitigative actions can be executed properly, the system's safety can be assumed. Performing each procedure, including supply chain, maintenance within a specified time, and maintaining product quality, carries enormous importance. The benefit of using FRAM is that time constraints for each function execution can be considered individually, and the resonance of missing time targets can also be predicted (Patriarca and Bergström, 2017). Industry can benefit from using such a model to know the required time constraints for individual functions and set pre-required functions accordingly. Also, barrier management or execution of safety functions can be planned therefore based on the weight of the function and their resonance effect of variability in the system.

It is possible to capture variability qualitatively, quantitatively, and dynamically by extended FRAM. The qualitative characteristics of variability can be observed in the visual model of FRAM both for functional output and for outcomes of the entire system. It allows one to capture and visualize functional output variation and understand the nature of functional output variables. Capturing qualitative variability characteristics can help analysts identify sources of variability that influence the output of downstream functions and the entire system. Coupled functions carry great importance as the variability can affect the output of upstream functions and affect related system goals capturing resonance of variability of function.

A prediction variability of a system goal can be expressed numerically by a safety index on a scale of 0 to 4. The numerical number represents a comparative number. However, from the analysis, it is visible that qualitative analysis helps the analysts most by giving critical insight into systems and required barriers. Apart from the variability of performance of related aspects, there can be many uncertainties in the system, affecting the system's performance. Quantitative analysis can compare the system performance at two different times or compare two similar systems. If the calculated safety index indicates the bad performance of the system, actions should be taken to improve the system.

Variability might occur as time variation can affect a function's output or the system's outcome. The model can capture time variation for a specific function and system. The execution time of the function is variable for various cases. The time variability may affect downstream functions in the transition process and may even influence the outcome of the entire system. Understanding time variations can help to improve the quality of the system.

A comparative analysis is done in the paper among extended FRAM, FRAM-STPA, Bayesian network, and bow-tie (Fig. 8). Methods are compared in terms of barrier allocation procedures, risk assessment procedures, competence in hazard identification, competence in barrier allocations, complexity, competence in identifying safety performance indicators, ability to represent complex relationships, acquaintance, and resource and time requirements. While comparing, extended FRAM is considered as described in this paper's method and case study section. The execution method of the FRAM-STPA method is described here, and a case study is presented in the supporting documents of the paper. A traditional Bayesian network and a traditional bow-tie method are considered for the comparison.

The detailed procedure of the FRAM method is described in Section 2 and is explained with a case study in Section 3 of the present paper. In the FRAM-STPA method, STPA keywords are used in the FRAM method

Table 3
Determining performance indicators from aspects of safety functions of FRAM.

Preventive Safety functions	Related aspects	Description	No	Performance indicator
Condition monitoring of pipe (CM)	Input functions	Assign related authority (AA)	1	Competence of authority
		Plan and follow a schedule (FS)	2	Frequency of CM
	Control	Management team	3	Competence of management team
		Maintenance team	4	Competence of maintenance team
		Supervisory control	5	Frequency of supervisory control
		Workplace environment	6	Number of periodical meetings between operators and supervisors
	Resources	Procedure	7	Number of existing procedures on condition monitoring, maintenance-inspection, insulation, operation
			8	Level of detail of each procedure
Do regular inspection and maintenance (RM)	Input functions	Develop schedule	9	Frequency of inspection
	Resources	Personnel (Maintain balance workload, communication, training)	10	Number of training for personnel training
			11	Level of detail covered for each training
		Procedure		
	Control	Supervisory control		
Insulate pipe (I)	Resources	Insulation guideline (FG)		
	Control	Third-party check (TC)	12	Level of detail check by the third party
Pipe design with proper specification (PD)	Resources	Employ efficient team (ET)	13	Competence of design team
		Follow standards (FS)	14	Level of detail of existing standards
Follow the correct operational procedure of STS (FOP)	Resources	Follow standards (FS)	15	Competence of operational team
		Employ efficient employees (EE)		
	Related aspects	Maintain balanced workload		
		Maintain a good work environment		
Keep external corrosion protection	Input functions	Give protection cover		
	Control	Inspection of external corrosion		
Keep internal corrosion protection	Resources	Use corrosion inhibitor		
Mitigative Safety functions				
To repair	Input functions	Assign personnel	1	Competence of repair personnel
		Train personnel	2	Training of personnel
	Control	Management team Maintenance team		
	Resources	Procedure	3	Number of existing procedures and manuals on repair and leak detection
			4	Level of detail of each procedure
Mitigate leak	Input functions	Detect leak		
	Control	Emergency rescue team	5	Competence of emergency rescue team
	Resources	Leak detector	6	Frequency of maintenance of sensors
			7	Frequency of replacement of sensors
			8	Calculated reliability of instrumented systems
		Mitigation procedure		
Mitigate further risk	Input functions	Prevent ignition		
	Control	Management team, Port authority		
	Resources	Deluge for cooling, fire detector, fire extinguisher, sprinkler, emergency rescue team		

to find deviations in the system. The first two steps of this method are similar to the FRAM method. Necessary functions related to the goal and related aspects and interconnections are determined similarly to FRAM. In the next step, deviations of functions and associated aspects are determined. Deviated functions and aspects cannot be marked as precise and proper. A function or an aspect may deviate due to deviation of downstream function or other aspects in the own function or other external aspects. Deviation of function or aspects may affect the system goals in various ways; for example, the system goal is not achieved at all or is not achieved precisely and on time.

Deviation of functions and aspects is identified by applying four key terms of STPA: A required function or aspect is 'not delivered at all, is 'delivered, but causes hazard', 'delivered too early or too late, 'stopped too soon or continued too long. Deviation of functions or aspects occurs due to a deficiency in establishing required safety constraints. Safety barriers are placed on establishing proper causal constraints. Upon failure of those barriers, constraints will not be fulfilled. So, the execution of the related function will not be executed. A FRAM-STPA model is constructed in this paper and presented in a supporting document. No distinction is made between system-level safety constraints and low-level safety constraints. The process model helps to identify causal factors and scenarios. After identifying process model scenarios, necessary safeguards are proposed.

A top event is identified in a traditional bow tie method (Mulcahy et al., 2017). Initiating events/threats and consequences for the top event are identified. Preventing barriers prevents the development of top events from threats (Hollnagel, 2016). Mitigating barriers are barriers to mitigate the effect of the top event to reduce consequences (Ruijter and Guldenmund, 2016). Physical, human, or organizational barriers can be distinguished (Sklet, 2006). The top event's risk can be evaluated by evaluating the performance of preventing and mitigating barriers. Intrinsic safety barriers can be identified to reduce the threats to the system.

A directed acyclic graph is constructed in a Bayesian network model where each node corresponds to a unique random variable. Each edge represents conditional dependency with a connected node. Barriers are

Table 4
Calculation of the possibility of achieving a target function without considering the coupling of performance deviation.

Safety function	Input functions	Weight	Var score			control	Weight	Var score			Resources	Weight	Var score			Effect score		
			Precise	at time t2	Not at all			Precise	at time t2	Not at all			Precise	at time t2	Not at all	Precise	at time t2	Not at all
Condition monitoring of pipe network (CM)	Assign related authority (AA)	3	0	1	4	Management team	3	0	1	4						0	3	12
	Plan and follow a schedule (FS)	3	0	1	4	Maintenance team	3	0	1	4						0	3	12
						Supervisory control	3	0	1	4								
						Workplace environment	3	0	1	4								
											Procedure	3	0	1	4			
	Performance score															0	9	60
	Scaled value															0	0,60	4
Do regular inspection and maintenance (RM)	Develop schedule	3	0	1	4	Supervisory control	3	0	1	4	Procedure	3	0	1	4	0	3	12
											Personnel (Maintain balance workload, communication, training)	3	0	1	4	0	0	0
	Performance score															0	12	48
	Scaled value															0	1,25	4

allocated to reduce the effect of the event or consequence node factors. Assessment in the Bayesian network follows two main steps. Building a directed acyclic graph is the first step. In the second step, conditional probability in each node is assessed for risk assessment of the system.

Hazard identification and mitigation are essential steps of any risk assessment method. The case study shows that both FRAM and FRAM-STPA can be used for hazard identification and mitigation. It is seen that both FRAM and FRAM-STPA can give a good overview of the scenario of system mishaps, and resisting barriers or functions can be better planned accordingly. Using probabilistic data to determine the variability score can evaluate the risk of a mishap. The probabilistic data can be collected from industry data for quantitative risk evaluation. In the present paper, probabilistic data for the assessment is avoided due to time constraints and limitations of the work’s scope.

Both FRAM and FRAM-STPA can give a quick way to check the adequacy of safety barriers. From the case study, it is easily visible that both FRAM and FRAM-STPA methods suggest an almost similar number of types and barrier elements required for the system. A significant advantage of the bow-tie model is that it is an easy and time-conserving model to identify barriers and assess risk in the system (Paltrinieri et al., 2019). The Bayesian network can also find the required barriers and determine the effect of the critical barrier in the system. A Bayesian network is built for a part of the case study for ’pipe condition, and a comparative analysis is made. The FRAM model considers the system’s status from downstream and upstream functions. Couplings of barriers or interaction of multiple barriers can also be considered.

Safety barrier performance indicators are determined by translating safety functions into measurable quantities. While translating, required input functions, resources, or controls are converted into quantifiable attributes used as indicators. FRAM gives a large number of leading indicators. Leading indicators are developed by extracting attributes related to the required safety function, which can perform the required safety function. In the present case, indicators are developed for only the safety functions of the system. The assessment gives 15 indicators, which indicates that many leading indicators will be found for the entire system. Development of lagging and leading indicators are developed separately. Lagging indicators are developed using the system’s variability of function and aspect. Leading safety performance indicators are developed in the Bayesian network by translating attributes of preventing and mitigative barrier nodes into measurable quantities (Fig. 9). The performance indicator of a node represents the performance of that particular barrier node. If performance improves, it will affect risk influencing factors to reduce the risk. For pipe network failure, performance indicators are developed using a Bayesian network and presented in a supporting document. Lagging performance indicators are developed to find frequency of events of safety barrier failures. For pipe network failure, 12 leading and 12 lagging indicators are found, similar to FRAM.

Risk assessment in the FRAM method follows a multilevel mathematical procedure. The variability and weight of the functions are determined using their performance at a specific time. The multilevel mathematical model uses all the assigned scores to find the overall safety index. The safety index represents the safety performance of the overall system. Experts assess weight value based on their expertise and knowledge during weight assignments. Each expert makes their assessment, and the safety performance of the overall system will be determined based on the assigned values. Subjective scoring is a limitation of presented extended FRAM. Different experts may give different scores due to having different educational and cultural backgrounds, work experiences, and familiarity with the project. If various experts are assigned, weighted average values can be used to score. Any mathematical model for risk assessment is not established in the earlier work of FRAM-STPA. Present papers also exclude the effort due to the limitation of the scope of the paper.

In Bayesian networks, A directed acyclic graph depicts a set of variables and their conditional dependencies (DAG). Bayesian networks are

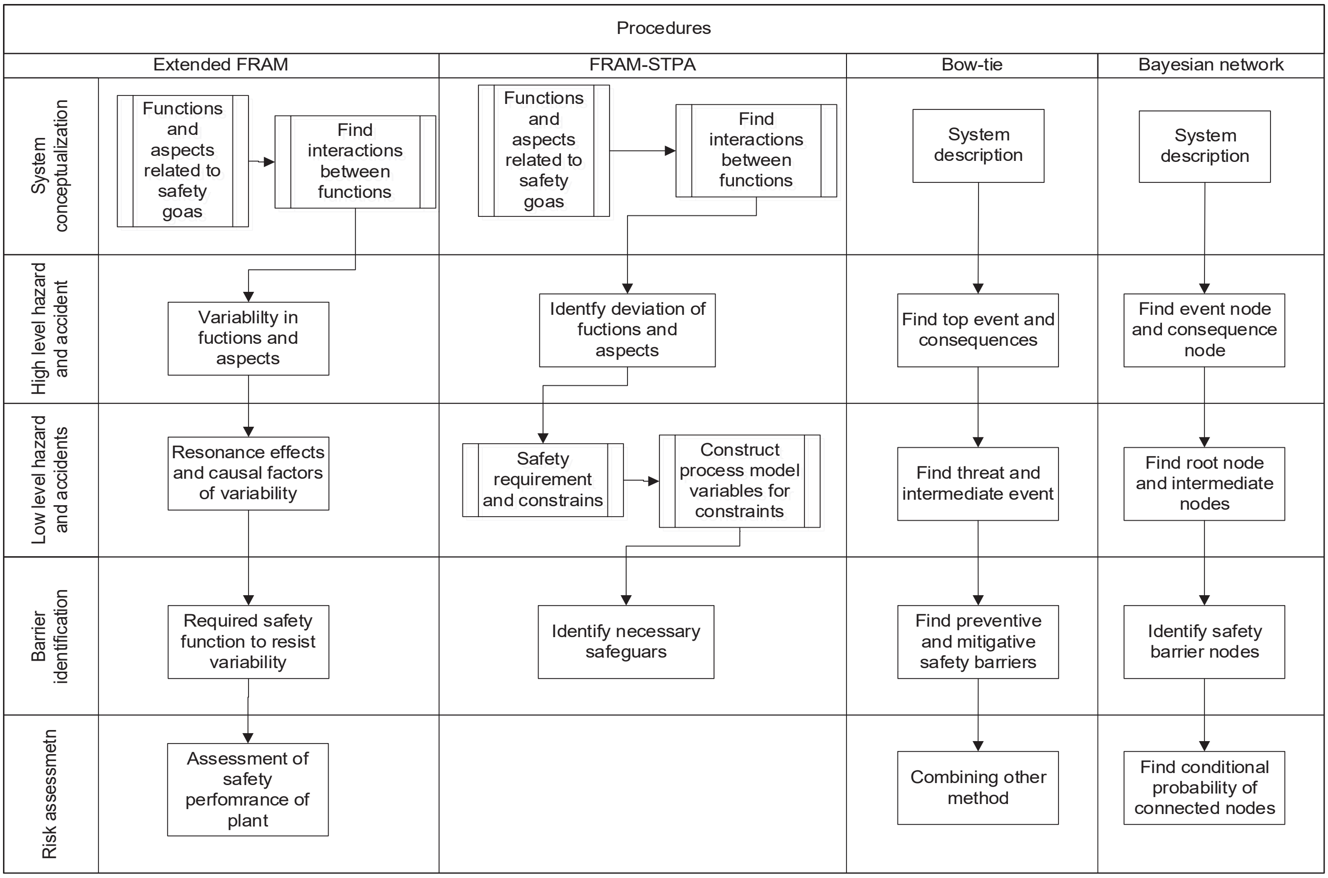

Fig. 8. Procedures of FRAM, FRAM-STPA, Bayesian, Bow-tie.

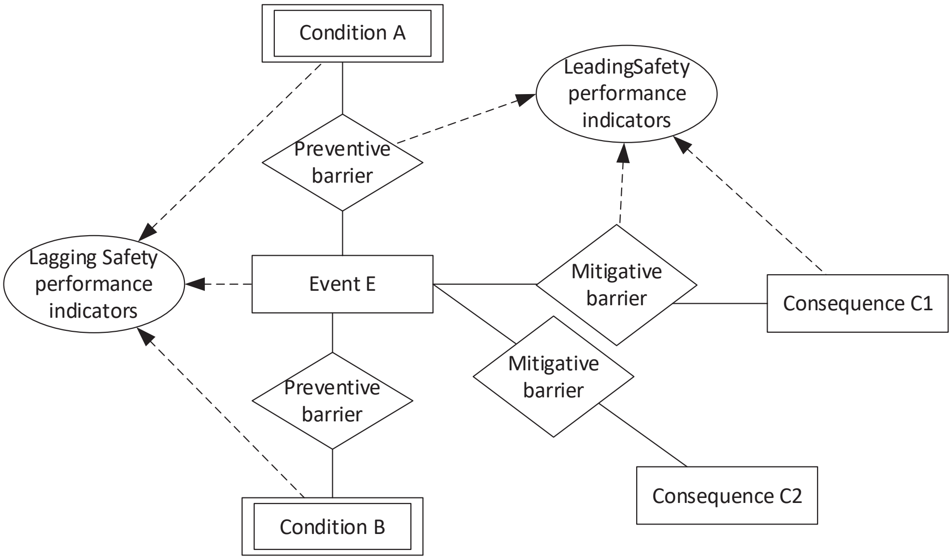

Fig. 9. Barrier allocation and developing safety indicators in the Bayesian network.

suitable for predicting the likelihood of an event knowing the dependence of associated variables affecting the occurrence of an event. Bayesian networks are ideal for forecasting the likelihood of an event knowing the dependency of related variables. A Bayesian network can represent the probabilistic relationships between variables and events. The network can compute the probabilities of the event given causes (Gregoriades and Mouskos, 2013). If an event node exists in the graph connecting random variables A and B, P(E|A, B) is a factor in the joint probability distribution.

In FRAM, resources and controllers are identified for each function execution. So, it can be visible which authority, procedure, or equipment should be assured for function execution. Also, FRAM gives dynamic analysis as it can consider time constraints. The Bow-tie model assumes an accident or mishap created from the contribution of a single threat or a barrier failure (Ferdous et al., 2013). It does not consider any coupling or interaction between threats or multiple barrier failure, which is a significant limitation in a bow tie. Bayesian network, probability function can be determined to find the relationship (García-Herrero et al., 2013). Change of status with time can also be captured (Yeo et al., 2016). a shortcoming of the Bayesian model is that, in this model, the allocation of tasks or authority of the task is not easily visible.

Compared to Bayesian, FRAM produces more specific details by considering the functional resonance process. Operations can be monitored to understand the entire system's performance once the functional model is constructed. Constructed models provide a basis for identifying potential pathways of both successful and unsuccessful operations. Capturing and interpreting performance variability helps to understand the yay that outcomes of a system (success and failures) are attainted. The study strives to capture variability's qualitative, quantitative, and dynamic characteristics. FRAM model is complex and very new to the industry. Analysts may find it challenging to build the model; hence it will take much time, which is a disadvantage of extended FRAM. Its time-consuming behavior is also proved by the earlier work of.

While determining quantitative performance scores in the extended FRAM method, the scaled value for each safety function is determined where safety functions and their relationship with related functions are relatively simple. For example, condition monitoring of a pipe network is connected to two input functions, four controls, and one resource, where they are linearly correlated. Relationships of other safety functions are considered linear here. Determining performance scores and scaling would be difficult where the relationship between functions and their downstream functions is very complex. The overall performance score is determined for only one required pre-condition to achieve the final goal. Determining the overall performance score for achieving the final goal considering all related input functions, pre-conditions, and resources, will be complicated and cumbersome and require many man-hours. Due to scope and time limitations, complete system analysis is kept out of the scope of the present paper. How to overcome this issue and develop computational tools can be further studied in the future. Involvement of other entities such as government authority, carrier authority, and regulatory authority in executing of function, how reluctance of action of such entities can affect the system's function and may initiate unwanted events are also kept out of the scope of the analysis.

In the FRAM-STPA method, violation of the safety constraints can be translated into risk influencing factors. The maintenance and organizational plans can be improved by considering related risk influencing factors. The bow-tie diagram is used widely in the industry to find the required safety barriers in the system. Bayesian network is also commonly used in industry and academia to show the connection between the system and risk influencing factors. However, considering multiple factors and complex interaction between factors considering each barrier's essential resources or controls gives quite a complex structure. This type of complex structure will take more resources and work hours.

5. Conclusion

This paper presented FRAM analysis for safety barrier management and system risk evaluation. The approach is applied for LNG ship-to-ship transfer operations. In addition, a comparison among bow-tie, FRAM-STPA and Bayesian networks are shown, along with the main conceptual differences between them. Comparison among various methods is based on their barrier allocation procedure, risk assessment procedure, competence in hazard identification, competence in barrier allocation, complexity, required time, and resources. FRAM shows the contribution of each element to the outcome of a function. It gives an idea of how to increase control measures of executing functions and other relevant requirements. The system's status is determined considered from downstream and upstream functions and their status.

The most dominant point in FRAM is that the method can consider the interaction between elements with time constraints, making it suitable for dynamic barrier management. Variability with more detail of the system is possible to extract from FRAM. FRAM possesses a better detail level than the Bayesian network and bow-tie. The paper identifies which functions have a more significant resonance effect in the system. The analysis presented in this article gives insight into how small imprecise or missing functions in the system may lead to substantial mishaps or performance deterioration. Extended FRAM in the presented work includes a semi-quantitative approach to enhance its capability to predict the system's performance.

Bayesian network and bow-tie model has been widely used in industry and academia to show the connection between hazard, consequence, and risk influencing factors. In a Bayesian network, a probability function can find the relationship. The Bayesian model can also consider the coupling of barriers or the interaction of multiple barriers. Change of status with time can also be captured. However, a shortcoming of the Bayesian model is that, in this model, the allocation of tasks or authority is not easily visible. Considering multiple factors and complex interaction between factors considering each barrier's required resources or controls gives quite a complex structure. A disadvantage of FRAM is that it is time-consuming, and presented mathematical analysis is complex. In future work, studying a complex socio-technical system, this type of analysis will help the analysts take the necessary steps to ensure safety and reduce system performance deviation. For example, installing an LNG network in a residential area where a slight deviation can significantly impact the company's reputation and economy.

There can be many types of variability in other systems, such as geographical territory, financial organization, and public administration. These types of systems will require distinct types of measures to prevent system degradation. Degradation relevant to these systems can be identified, and FRAM can be utilized to check measures to avoid such degradation. The consequence of the absence of any measures can also be predicted. Such analysis can be studied in the future. Accidents often occur due to a lack of training and resources in these socio-technical systems. It is possible to find out these lacking by finding required resources or pre-conditions relevant to each function. Many institutions get involved in large-scale projects such as flood prevention, war recovery, and nuclear safety. Often accidents occur from a lack of action from government bodies and related institutions. FRAM can cover the role of various entities. Required actions that the government or related authority should take can be identified, and the consequence of missing action can be predicted. However, a more sophisticated model should be developed to find missing actions from each organization. Future work is needed to understand better and predict these issues. A comparison of various methods in the present paper is made based on the assessment of the LNG STS system, which is quite simple. A complex system may provide various other perspectives on the comparison.

CRediT authorship contribution statement

Sharmin Sultana: Conceptualization, Methodology, Software, Writing – original draft. **Stein Haugen:** Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Sharmin Sultana reports financial support was provided by Research Council of Norway. Sharmin Sultana reports financial support, administrative support, and article publishing charges were provided by DynSoL AS. Sharmin Sultana reports a relationship with DynSoL AS that includes: employment.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary material

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