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Enhancing emergency response planning for natech accidents in process operations using functional resonance analysis method (FRAM): A case of fuel storage tank farm

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A R T I C L E I N F O

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A B S T R A C T

Recent increases in climate-induced natural disasters have amplified the risk of Natech (natural hazard-triggered technological) accidents, particularly in the chemical industry. These emergencies, characterized by their urgency and resource constraints, pose significant challenges for emergency planning. The Functional Resonance Analysis Method (FRAM) offers a systematic approach to enhance emergency response strategies. This study introduces a FRAM-based methodology specifically designed for fuel storage tank farms, structured into four critical stages: understanding, designing, analyzing, and enhancing the response process. It promotes a cycle of continuous improvement. A case study on a seismic Natech incident at a fuel storage facility demonstrates the methodology's effectiveness and its potential to boost the resilience of emergency response systems against Natech challenges.

1. Introduction

Natural hazards, such as earthquakes, floods, and hurricanes may trigger a technological accident, such as substance release and equipment damage. This accidental scenario is defined as Natech accidents, that is, technological accidents triggered by natural hazards (Caratozzolo et al., 2022; Showalter and Myers, 1994); Natech accidents represent a fusion of the immense natural forces and the potential technical risks associated with industrial operations. These accidents exhibit distinctive traits, which encompass: i) a synergistic and cross-sectoral impact, ii) complexity, iii) unpredictability, and iv) the potential for cascading effects. Natech accidents have become a growing concern in the last decades. On the one hand, enormous studies have indicated a significant increase in the frequency of Natech accidents' incidence due to growing industrial development and climate change (Krausmann et al., 2011; Misuri and Cozzani, 2021; Ricci et al., 2021; Sengul et al., 2012). According to Krausmann et al. (2011), about 2–5 % of industrial accidents reported in the main European industrial-accident databases resulted from natural hazards. On the other hand, the consequence of the Natech accidents is more severe than the conventional technology accident (Gao et al., 2022; Misuri et al., 2021b; Zeng et al., 2022). Because the interaction between natural hazards and industrial installations may result in severe conjoint threats.

Particularly in the process industries, interconnected industrial installations, such as storage tanks, and piping systems are vulnerable to natural hazards (Caratozzolo et al., 2022; Khakzad and Van Gelder, 2017; Lan et al., 2022). In addition, natural hazards may destroy the safety system of a chemical plant, reducing its capability of accident mitigation (Camila et al., 2019; Di Maio et al., 2023; Krausmann et al., 2011). Accordingly, a Natech accident may damage multiple industrial installations and increase the possibility of accident propagation by a cascade effect. For instance, the flooding triggered by Hurricane Harvey (2017) damaged oil storage tanks and the power system in a chemical plant, leading to multiple oil spills, chemical decomposition, and fires (Qin et al., 2020; Samon et al., 2022). Moreover, chemicals are inflammable, explosive, and toxic. Once multiple simultaneous chemicals are released in a Natech accident, multiple fire and/or explosion scenarios may develop, and fire may spread to nearby industrial installations, amplifying the consequence of a Natech accident (Naderpour and Khakzad, 2018).

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Due to the serious consequences of Natech scenarios in the chemical industry, emergency response plays an important role in the framework of risk management (Ricci et al., 2022). In the emergency response process, a series of interactive technical and social actions such as evacuation, medical aid, clean-up, combating a fire, and securing a leak, are conducted to protect human health, the environment, and facilities. Therefore, the emergency response process can be regarded as a complex socio-technical system, that is, social and technical aspects engaged in goal-directed behavior (Sony and Naik, 2020). An effective emergency response process can reduce the consequences of Natech accidents and limit the probability of its escalation (Misuri et al., 2021b; Zhou et al., 2016). However, natural hazards may hinder and destroy the emergency response system, failing the technical barriers and equipment (Krausmann et al., 2016; Lindell and Perry, 1996). Moreover, Natech accidents may affect a wide area. Protecting human health, the environment, and the facilities in this area may limit the availability of emergency resources (Krausmann and Cruz, 2013). These can affect the effectiveness of the emergency response in a Natech accident. Therefore, it is essential to design and analyze the emergency response from a systematic perspective.

Although the emergency response plays an important role in the mitigation of Natech accidents within fuel storage tank farms. Limited studies focusing on the emergency response process for Natech accidents are available (Bernier et al., 2019; Krausmann et al., 2011; Lan et al., 2022). Most of these studies predominantly concentrate on either preemptively designing emergency responses for Natech accidents or drawing insights from post-incident emergency response experiences. There has been a notable gap in the analysis and improvement of response performance during its operational phase, garnering limited attention. This oversight is significant as the emergency response process, developed under time and information constraints, may prove inadequate. Moreover, Natech accidents typically exhibit dynamic evolution, necessitating continuous adjustments to the functions and coupling relationships within the emergency response process. In addition, despite the critical role of emergency response in Natech accidents at fuel storage tank farms, there is a notable scarcity of studies addressing emergency response planning in this context. Hence, there is a critical need to establish a continuous improvement framework for emergency response planning during operation.

Building upon the above analysis, this paper aims to develop an approach for emergency response planning tailored to Natech accidents, exemplified through a case study on fuel storage tank farms. The proposed method outlines four key stages in emergency response planning: understanding, designing, analyzing, and enhancing the emergency response process, all assessed through the application of the Functional Resonance Analysis Method (FRAM). This method defines socio-technical systems from a systemic perspective, ensuring its efficacy in identifying, analyzing, and managing functions and their variability within the emergency response process. Furthermore, in the proposed approach, the stages of understanding, designing, analyzing, and enhancing the emergency response process constitute a cyclical framework. This iterative process facilitates continuous improvement by uncovering negative performance variability and devising corresponding enhancement strategies.

The following sections of the paper are organized as follows. The relative knowledge of FRAM is introduced in Section 2. The approach proposed for emergency response planning for Natech accidents is described in Section 3. A case study of emergency response to seismic Natech accidents in fuel storage facilities is presented in Section 4. The conclusions are reported in Section 5.

2. Literature review

2.1. Emergency response process for process industries

An accident in a process industry area may lead to economic, environmental, and social losses in a very short time. The emergency response process is quite important to ensure the safety of a process industry area. To this end, many studies focused on emergency response planning and management for technical accidents and/or Natech accidents in a process industry area.

The emergency response process for technical accidents in a process industry area attracted great attention. Rebeeh et al. (2019) introduced an LHI (location hazard index) and the response time optimization model-based emergency response management system for a petrochemical fire, which considered the prioritization of hazards, response time, and available response resources. Zhou et al. (2016) introduced an event sequence diagram-based methodology to analyze the efficiency of the different emergency response actions in preventing or delaying fire-induced domino effects in a fuel storage plant. To improve emergency response planning for chemical spills, Zhao et al. (2019) utilized process mining techniques to analyze the emergency response tasks and the cooperation of the emergency-response actors. Zhou and Reniers (2021) utilized petri net simulation to analyze the effect of the different arrival times of the emergency teams on the failure time of adjacent facilities in multi-department emergency response and applied it to a tank fire accident to show its efficiency. Wang et al. (2024) utilized the isomorphic Markov chain analysis approach to analyze the efficiency of the emergency response process for hydrogen leakage and explosion accidents.

There is a growing concern over the emergency response process for Natech accidents in a process industry area. Bernier et al. (2019) developed a scenario-based framework to analyze the potential Natech accidents triggered by the storm at the petrochemical storage tank farm and the accessibility of petrochemical facilities by emergency responders. For Natech scenarios, Ricci et al. (2024) introduced a technical methodology to analyze the performance of emergency response, to identify the phases of emergency response that are mostly affected by natural events, and to evaluate the time to carry out the emergency response. Baser and Behnam (2020) introduced a framework to develop an emergency response plan for seismic Natech accidents at a fuel storage farm. Misuri et al. (2021a) investigated the Saga prefecture oil spill triggered by the flood and corresponding emergency response action to identify the gaps in Natech accident management. Krausmann et al. (2011) investigated about 1000 Natech accidents that occurred in chemical facilities such as tanks, reactors, pipelines, and compressors and gave some recommendations for emergency response planning.

As analyzed above, the studies related to technical accidents are conducted from the perspective of how to develop, analyze, and improve an emergency response plan from a systematic perspective. However, the studies related to Natech accidents are mainly conducted from the perspective of analyzing the effect of Natech accidents on emergency response plans, such as the effect of Natech accidents on accessibility of resources, and the emergency response phase mainly affected by natural events. This may limit performance improvement of emergency response in a Natech scenario. The studies related to the emergency response process for technical accidents form the basis for forming and improving emergency response plans for Natech accidents.

2.2. Functional resonance analysis method

FRAM, introduced by Hollnagel (2012), is a qualitative method for modeling socio-technical systems. It defines a system in terms of a series of activities represented by coupled functions. This enables FRAM to provide deep insight into how an intractable, complex, and dynamic socio-technological system functions (Smith et al., 2017). A FRAM analysis is conducted based on four steps, namely identifying and describing the functions, characterizing the variability of each function, aggregating the performance variability, and consequences of the analysis (Hollnagel, 2012).

The FRAM is built on four principles, namely emergent outcomes, functional resonance, the equivalence of failures and successes, and approximate adjustments (Hollnagel, 2012). According to FRAM, the outcome of a system emerges from the aggregated performance variability of functions (emergent outcomes and functional resonance). Specifically, functional resonance can be defined as the detectable signal that emerges from the unintended interaction of the variability. FRAM uses functional resonance as a way to understand outcomes that are both non-causal (emergent) and nonlinear (Hollnagel, 2012). FRAM admits the duality of performance variability as a consequence of the aggregated system functionality, and not by defining outcomes from individual functions as desirable or undesirable in isolation (equivalence of failures and successes). Therefore, the main purpose of FRAM is to monitor and manage performance variability rather than merely limit, control, or reduce performance variability (Grabbe et al., 2020). From a FRAM perspective, it is important to understand how performance is managed and can be adapted even during operations (approximate adjustments).

Due to the efficiency of FRAM in modeling complex socio-technological systems, it has been utilized in various fields, such as healthcare (Buikstra et al., 2020; O'Hara et al., 2020), transportation (Adhita et al., 2023; Huang et al., 2019), and chemicals (Yu et al., 2021, 2020). In particular, FRAM has attracted enormous attention to improve safety in the chemical industry. Sultana and Haugen (2023) utilized FRAM to identify the potential functional resonance in the liquified natural gas ship-to-ship transfer process and developed safety barrier systems for variability management. Zinetullina et al. (2021) evaluated the resilience of chemical process systems by FRAM and dynamic Bayesian networks (BN) to ensure the safety and functionality of the system. Salihoglu and Besikci (2021) investigate the prestige oil spill accident by utilizing FRAM to model the system's function and variability. Yu et al. (2021) utilized FRAM to model the functional coupling and to identify the paths resulting in potentially hazardous scenarios in the polymerization process in the process industry. Ma et al. (2023) identify the functions in the hazardous chemicals maritime transportation system and evaluate the risk resulting from the failure coupling links between functions by FRAM and a risk matrix. These FRAM analyses have shown the advantage of revealing a system's workings and mechanisms.

Owing to the high frequency and risk of industrial accidents, several studies conducted a FRAM analysis for emergency response processes. Qiao et al. (2022) analyzed the resilience of the emergency response system for maritime incidents in the process of transporting liquid cargo by a FRAM and Bayesian network (BN)-based model. Liu et al. (2024) combined FRAM and reinforcement learning to update and optimize the emergency response process for blowout accidents. Steen et al. (2021) utilized FRAM to explore the adaptability and evolution of relationships among functions in the emergency response process and applied to the condensate leak incident in the Gjøa field. FRAM has a great advantage in modeling the complex emergency response process in high-risk scenarios for the chemical industry because of its powerful description of emergent system behavior. However, to the authors' knowledge, a FRAM analysis of emergency response processes has not been specifically applied to Natech accidents.

The emergency response system related to Natech accidents consists of multiple functions with nonlinear coupling relationships. Despite the high risk and complexity of such accidents in the chemical industry, both emergency response resources and time are limited. FRAM is capable of functionally understanding the emergency response process for Natech accidents, while dynamically adjusting it to the context for a better protection of humans, facilities, and the environment.

3. The proposed approach for emergency response planning for Natech accidents

Natural hazards are inherently unpredictable, rendering emergency response planning not only evident but also absolutely essential for mitigating the impact of Natech accidents. Nonetheless, the task of ensuring the quality and effectiveness of such planning is fraught with challenges, primarily stemming from two essential sources of uncertainty. First and foremost, Natech scenarios are often difficult to specify due to limited available information, leading to a disparity between anticipated and actual events. Additionally, the stochastic and uncertain nature of operational conditions further compounds these challenges. Therefore, rapid adaptability in emergency response processes is quite essential.

Given the irregular performance and the need for rapid adaptability in such processes, qualitative analysis offers the flexibility and efficiency required for timely and effective response planning. To this end, the FRAM-based approach is constructed to qualitatively analyze the performance variability inherent in emergency response planning and to enhance it through targeted adjustments. Triggered by the plan-do-check-act (PDCA) improvement circle, Fig. 1 illustrates a continuous improvement cycle encompassing stages of understanding, designing, analyzing, and enhancing emergency response planning for Natech accidents occurring at fuel storage tank farms. The duration of this continuous improvement cycle is an iterative design cycle.

This section introduces a method founded on the FRAM to implement this iterative cycle effectively. By doing so, it provides a structured framework for managing and continuously improving emergency response planning in the face of unpredictable natural hazards and Natech scenarios.

3.1. Understanding the emergency response process

In Natech accidents, the primary objective of emergency response is to safeguard human health and safety, minimize environmental impact, and restrict facility damage through meticulous planning, preparedness, resource coordination, and long-term recovery efforts. This multifaceted emergency response process encompasses various functions, making it imperative to comprehend and analyze these functions in order to enhance overall preparedness and effectiveness. Task analysis can be an effective way for the purpose of identifying FRAM functions (Hollnagel, 2012). Task analysis studies what should be done to achieve specific aims. Each action in a task can be treated as a function (Hollnagel, 2012). According to (Ricci et al., 2022), the emergency response process can be considered a risk management process. The risk management process consists of risk identification, evaluation, and control (Yang et al., 2018), which correspond to the task types of mobilization, alert, and combat in emergency response depicted in Fig. 2.

3.1.1. Mobilization tasks

Fuel storage tanks are notably susceptible to the impact of natural hazards, thereby elevating the potential for cascading events that could compromise the emergency response systems of a storage tank farm. Consequently, the involvement of external resources is essential in Natech accidents. As the initial responders, operators of a storage tank

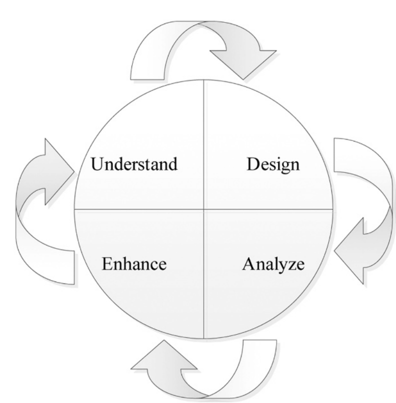

Fig. 1. The diagram of the proposed visual method.

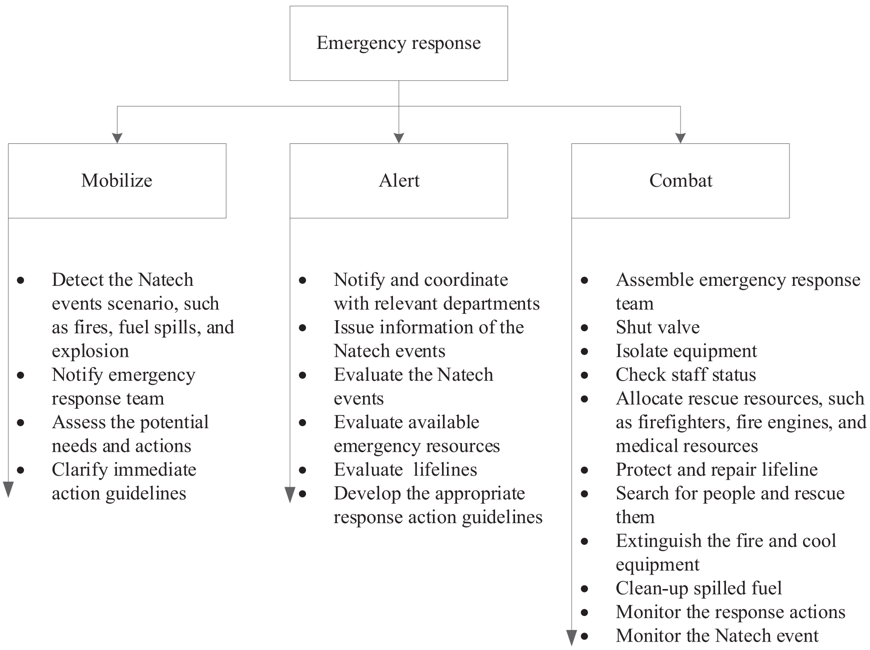

Fig. 2. A hierarchical task analysis of the emergency response process for function identification by task types.

farm face the critical responsibility of swiftly assessing the situation and formulating immediate action plans for mobilization tasks. Within this context, operators execute prompt actions, which can be represented by functions within the FRAM. Such functions may involve actions like valve closure and equipment isolation.

3.1.2. *Alert tasks*

Moreover, operators are required to promptly notify coordinating organizations, such as regional crisis centers, with whom they collaboratively formulate comprehensive response guidelines from a systematic perspective. This collaborative endeavor involves evaluating various critical aspects related to emergency response, including: i) the projected consequences of Natech accidents, ii) the accessibility of emergency response resources, encompassing physical equipment, responders, and vital information, among other factors, and iii) the condition of lifelines, such as transportation systems, power grids, and information networks.

3.1.3. *Combat tasks*

In the ensuing combat task, various organizations engage in a series of actions (functions) delineated in the guidelines to fulfill the objectives of emergency response. These actions may encompass tasks such as extinguishing fires, conducting rescue operations, and overseeing fuel cleanup, among other crucial activities.

In summary, this text delineates the overarching functions encompassed within an emergency response process, as visually depicted in Fig. 2.

3.2. *Design of the emergency response process in Natech accidents*

The current phase is focused on the design of the emergency response process, which involves the qualitative definition of how each function should operate effectively. In a Natech scenario of a storage tank farm, the simultaneous destruction of multiple fuel storage facilities and lifelines can give rise to multi-source accident scenarios and rapid propagation patterns. It is essential to design the emergency response process from a systematic perspective. Therefore, this study employs the FRAM as a tool for designing emergency response planning. This approach is chosen to ensure the quality and reliability of response measures, particularly when faced with constraints of time and available resources. The subsequent discussion delves into these concepts in greater detail.

FRAM characterizes a function per definition from the aspects of Input (I), and Output (O) and if relevant also from the aspects of Preconditions (P), Resources (R), Time (T), and Control (C). Notably, the last four aspects enable FRAM to support the design of functional reliability or redundancy in the emergency response process for Natech accidents in a storage tank farm.

- The Preconditions (P) are the conditions that must exist before a function is executed. However, in the emergency response process, the Preconditions (P) of a function may be disregarded due to not knowing what to verify and/or subjectively deciding to disregard. FRAM helps to clarify the preconditions of each function and urges to verify these preconditions in the emergency response process.
- The Resources (R) is what the function needs when it is carried out. During execution, a function utilizes resources, such as manpower, equipment, materials, information, energy, etc. In Natech accident scenarios, emergency response facilities can be damaged, leading to limited availability of fire-control equipment, firefighters, electrical equipment, etc. Time pressure adds another challenge to making a proper decision, given the limited accessibility to required data. When time also fulfills the purpose of a resource, the resource is given priority of the aspect label. FRAM visualizes the interdependency of Resources (R) of each function in the emergency response plan. It helps minimize resource allocation conflicts between functions through proper coordination.
- The Time (T) is the temporal constraints that affect the function. Natech accidents propagate and typically cascade fast. In responding to such an accident, the Time (T) of each function in emergency response should be given great importance. FRAM characterizes Time in ways that can affect the execution of a function in the emergency response plan. Time can be an expression of the duration of an output function or relative timing conditions, or triggers (earliest/ latest starting/ ending time).
- The Control (C) is how the function is monitored or controlled. The work condition of the emergency response process varies temporally and spatially. Each function of the emergency

response process needs appropriate adjustments. Supervising or regulating what is produced by a function plays an important role in ensuring desired output. FRAM defines this as Control (C) for each function, which includes regular instructions, standards, a schedule, a plan, a procedure, etc. Usually, Control (C) of a function can be carried out by the entity responsible for the function's realization or the other functions.

FRAM is adept at characterizing the interaction between functions through coupling relationships. This stems from the logical consequence that the output of a function serves as at least one aspect of its downstream function, encompassing Input (I), Preconditions (P), Resources (R), Time (T), and Control (C). This capability allows FRAM to discern various relationship types among functions, such as causal, temporal, control, change, etc., thereby minimizing the risk of misunderstandings in the coupling relationships within the emergency response process. The above introduction about the aspects of FRAM helps to understand the coupling relationship. Additionally, FRAM defines coupling relationships by considering functions necessary for achieving the emergency response process's objectives, the influence of one function on others, and the integration of functions to attain the specified goals.

Based on the functions shown in Fig. 2, a FRAM model for the emergency response process for responding to Natech accidents in a storage tank farm is shown in Fig. 3.

3.3. Analysis of the emergency response process in Natech accidents

The primary objective of this stage is to scrutinize the performance of the emergency response process in Natech accidents. Triggered by a means-end analysis, a hierarchy of the performance index system is established. A means-end analysis is hierarchical, where means serve certain ends that in turn serve as means to higher-level ends (van Rekom and Wierenga, 2007). In other words, the target of a system can be divided into the target of its sub-system. Therefore, the hierarchy of the performance index system for performance variability analysis is established as follows. In Section 3.2, the focus lies on crafting a dependable emergency response process. This process, in turn, is further subdivided into three distinct task types: mobilization, alert, and combat. Following the framework presented in [4], each task type encompasses two function types: main and auxiliary function types. The main function type is those directly linked to achieving the target, while the auxiliary function type supports the execution of the main function type. Consequently, in the hierarchy of the performance index system, the initial level index revolves assessing the reliability of the emergency response process. The second-level index revolves around assessing the performance variability of these main function type within each task type, while the third-level index pertains to evaluating the performance variability of the auxiliary function type.

Regarding the identification of the main function type, the principles differ across the three task types. In the mobilization and alert task types, their role primarily involves initiating and guiding subsequent task types. Consequently, the main function type within these two task types are those that establish crucial connections with numerous functions in downstream task types. In contrast, the combat task type primarily aims to achieve the ultimate objective of the emergency response process. Consequently, main function type within the combat task type are those directly related to this overarching goal. These functions may encompass activities like searching for and rescuing individuals, extinguishing fires, cooling equipment, and managing fuel spills.

As for performance variability, phenotypes of each function's output may differ due to the differences among functions' roles in the emergency response process. According to (Hollnagel, 2012), performance variability can be characterized by speed, distance, sequence, object, force, duration, direction, timing, etc. For instance, a hierarchy of performance index systems is constructed for the emergency response process, as shown in Fig. 4.

Following the establishment of the performance index system, the next step involves a comprehensive analysis of the performance variability of the main function type. When instances of suboptimal performance within these functions are identified, it becomes imperative to discern the underlying causes. Generally, underperforming functions can be attributed to either intrinsic issues within the function itself or unexpected functional resonances introduced by the aggregation of several functions.

In those cases where the function itself is the source of the problem, a thorough examination of its inherent nature is conducted. Conversely, when the source of undesirable system behavior as a result of functional resonance, a follow-up assessment is undertaken. This involves identifying all upstream functions, which encompass both main and auxiliary function types, linked to the functions exhibiting suboptimal performance. Subsequently, the performance variability of these related functions is closely scrutinized, with the aim of interpreting the reasons behind the negative performance, utilizing functional resonance analysis.

3.4. Enhancement of the emergency response process in Natech accidents

The primary objective of this stage is to improve the emergency response process, drawing upon the insights derived from the performance analysis of each function. As previously mentioned, unsatisfactory performance within functions may stem from either inherent issue within the function itself or unforeseen functional resonance, which

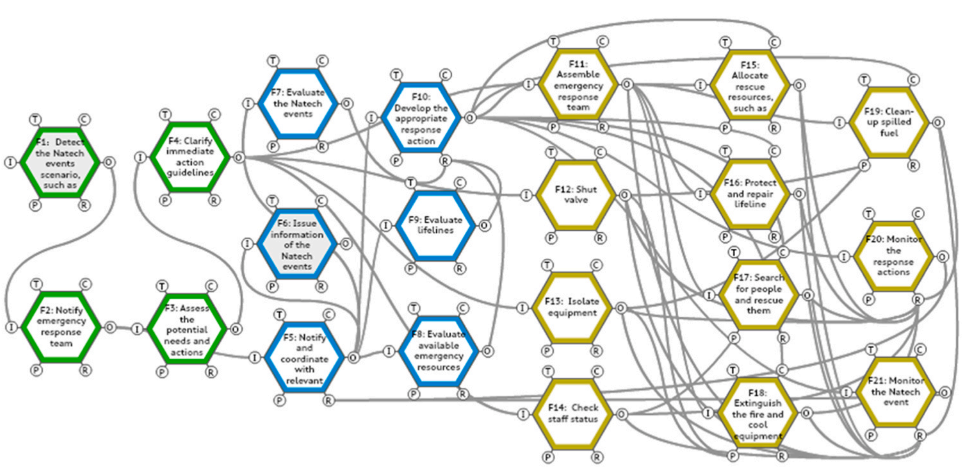

Fig. 3. The diagram of a general emergency response process.

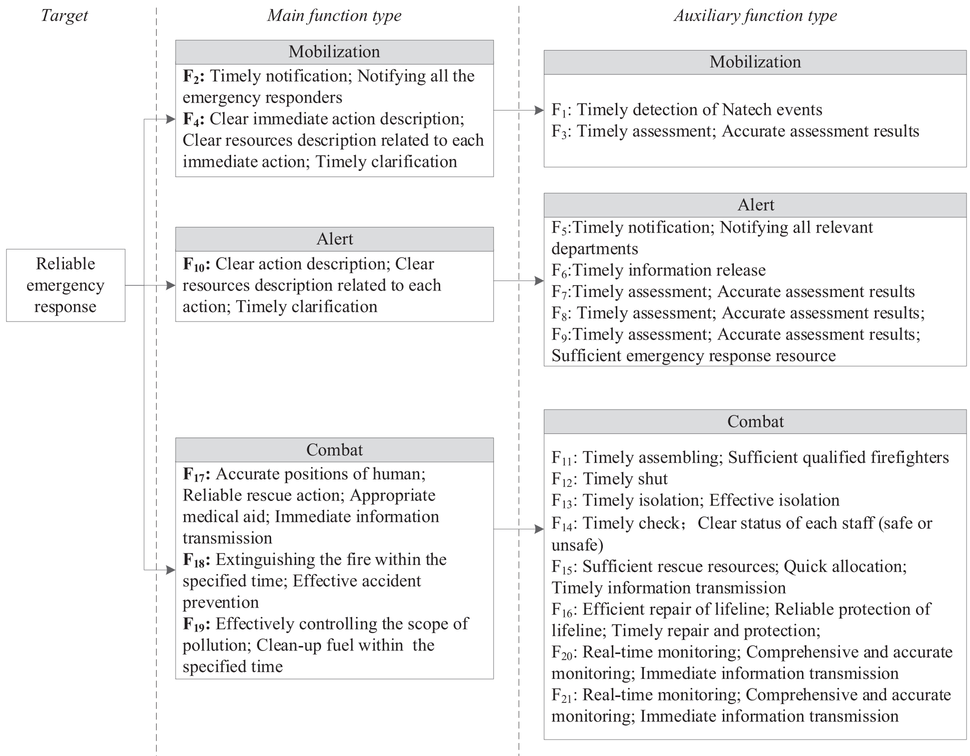

Fig. 4. The hierarchy of the performance index system.

involves interconnections among multiple functions, potentially magnifying performance variability in several functions.

Of particular note, unexpected functional resonance entails a coupling effect among multiple functions, further emphasizing the importance of effective performance variability management. In essence, the core of enhancing the emergency response process lies in the development of appropriate strategies for the management of performance variability.

Based on the preceding analysis, strategies for managing performance variability can be crafted from two distinct perspectives. First, there is the option to develop performance variability management strategies from a functional standpoint. This involves meticulously designing the function's nature to facilitate its realization. This design may encompass entities like technology, human resources, and organizational structures, which are responsible for executing these functions. These entities can be adjusted in response to specific scenarios. Moreover, the adaptability of the emergency response process can be enhanced by introducing new functions to address the evolving work conditions or unforeseen emergencies.

In addition, it is imperative to approach performance variability management from a systematic viewpoint. Within the emergency response process, multiple functions work in concert to achieve a defined objective, and they must be systematically fine-tuned. For example, the collaboration among a series of functions can be shifted from sequential execution to parallel execution, guided by their coupling relationships. Consequently, adjustments to the coupling relationships between functions become essential. This entails both adding and removing such relationships while modifying the performance variability aspects that the upstream function contributes to the downstream function.

4. Case study

In this section, the FRAM method and the performance index approach are applied to a case introduced by Baser and Behnam (2020) to show the efficiency of the proposed method, where an emergency response plan is developed to respond to a fire in a fuel storage facility caused by a seismic Natech accident.

4.1. Description of the seismic Natech accident in the fuel storage tank farm

The fuel storage tank farm, situated in a seismic region with a Peak Ground Acceleration (PGA) of 0.4 g, was established over 50 years ago. This facility serves as a storage hub for various oil products, including Mazut and other petrochemical feedstock (Baser and Behnam, 2020). The facility layout, depicted in Fig. 5, features 20 tanks arranged within a common bund wall, further subdivided into eight groups, with strategically positioned access routes between the primary bund walls. Several primary imperfections within the fuel storage facility intensify the risk of tank or pipe failures in the event of an earthquake. Firstly, transmission pipes traverse the bund walls, creating a potential for unharmonious oscillation between the pipes and the walls, thereby increasing the risk of pipe fractures during seismic activity. Secondly, platforms or ramps constructed over the pipes within the bund wall for vehicular traffic pose a heightened threat of severe damage to the tanks or piping systems during an earthquake. Lastly, a notable concern is the absence of mechanical anchors on the tanks, a factor that may elevate the risk of failure, particularly for tanks exceeding 50 years in service. Addressing these vulnerabilities is imperative to enhance the seismic resilience of the aging storage facility.

These facility imperfections significantly heighten the likelihood of leakage from the bund wall, particularly at their joints with the pipes, making it a highly plausible failure scenario, particularly in seismic events (Baser and Behnam, 2020). In such circumstances, the impact of the roof against the tank wall could easily trigger a fire on the surface of a floating roof tank. To assess the potential consequences, Baser and Behnam (2020) identified and defined five fire scenarios initiated by earthquake-induced events. These scenarios were meticulously modeled using Process Hazard Analysis Software (PHAST). The modeling

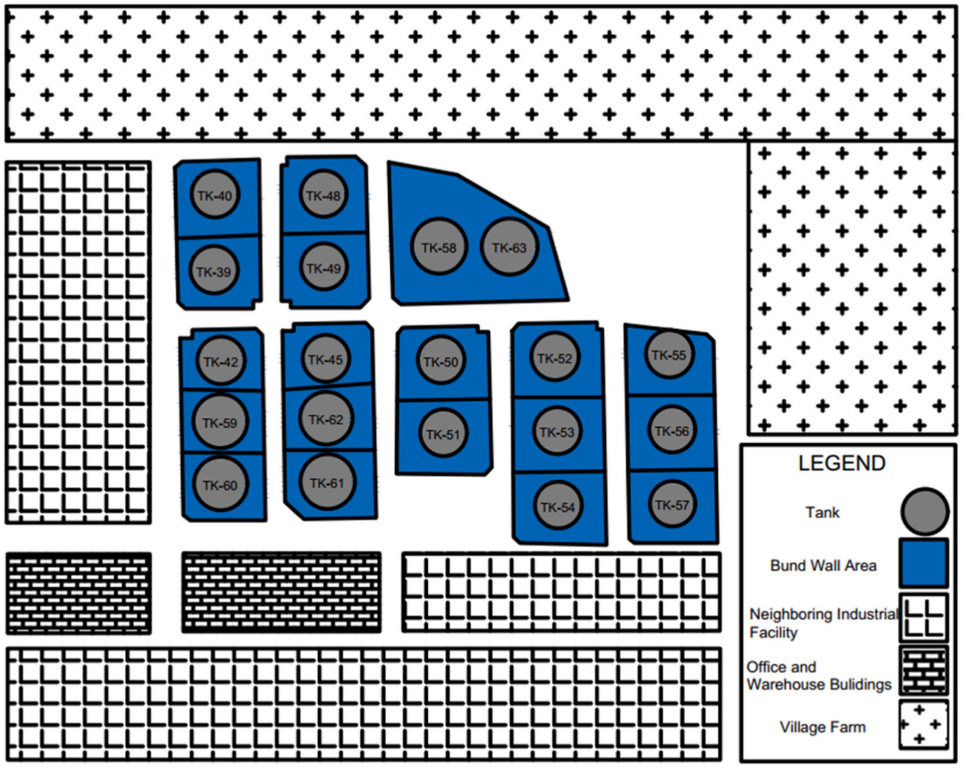

Fig. 5. The layout of the tanks.

outcomes highlight a particularly alarming scenario, wherein the worst-case fire risk emerges in the bund wall of tanks 52, 53, and 54. This scenario is characterized by the centrality of these tanks, significant decay in the tanks' structural integrity, heightened ignitability of the fuel within the tanks, and the inadequacy of the bund wall's capacity. The culmination of these factors significantly amplifies the associated risks in this specific scenario.

The fires in the bund wall of tanks 52, 53, and 54 may throw off huge amounts of radiation, leading to the failure of multiple facilities. The amount of radiation received by facilities from the fire is affected by many factors, such as the distance between facilities, climatic conditions, etc. According to the layout information and the climatic condition information given by Baser and Behnam (2020), the radiation received by surrounding tanks from the fire can be determined, which is shown in Fig. 6. In Fig. 6, the red numbers indicate the radiation received by each tank from the fire in kw/m^2. The yellow numbers indicate the distance between the tank and the fire in m. As shown in Fig. 6, the radiation received by Tank 52, 53, and 54 is 20 kw/m^2 and the radiation received by Tank 50, 51, 55, 56, 57, 58, and 63 is 4.0–10.0 kw/m^2. Referring to the connection between the tanks time to failure and the radiation received from fire (Cozzani et al., 2006), the failure time of Tanks 52, 53, and 54 is about 500 s and the failure time of Tanks 50, 51, and 55, 56, 58, and 63 is about 2000s to 7000 s. Such a risk scenario may use 68000 L of 3 % foam concentrate and 2200000 L of water.

For such a risk scenario, Baser and Behnam (2020) formulated an emergency response plan only considering the destruction of the fire water network within the fuel storage tank farm. A seismic Natech accident in a fuel storage tank farm may impact the other types of facilities. In addition, the initial plan introduced by Baser and Behnam (2020) merely enumerated specific actions without a detailed analysis of their efficacy and interrelationships. The lack of comprehensive information renders the case insufficient to validate the proposed approach and demonstrate its advantages. To address this limitation, our study is grounded in three hypotheses: (i) Inefficient communication between

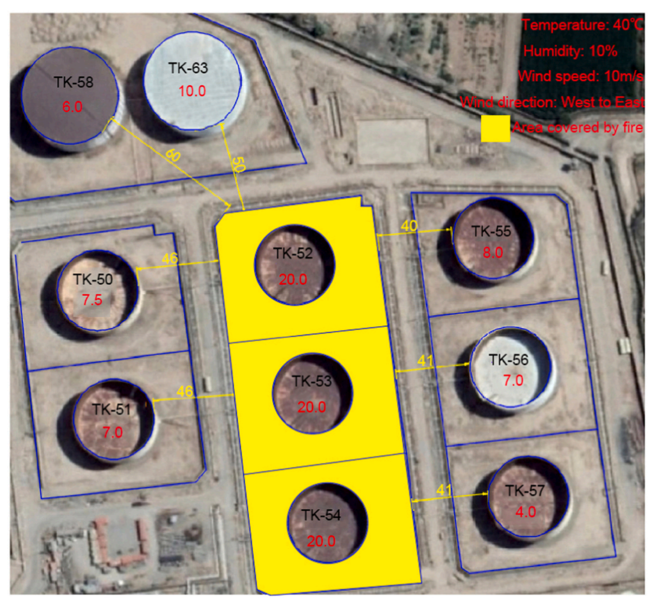

Fig. 6. The radiation received by surrounding tanks.

the staff in the fuel storage tank farm and the firefighters at the onset of the emergency, and (ii) Limited availability of firefighters for emergency actions. (iii) Severe damage to communication facilities.

4.2. Application of the proposed approach

The proposed method for developing an emergency response plan unfolds in the following manner. This section repeats the continuous improvement cycle twice to show how to dynamically adjust an emergency response plan.

4.2.1. The first round of emergency response planning

In the understanding stage, all functions in the emergency response process are identified. As mentioned above, the Natech accident in the fuel storage tank farm emerged as a fire in the bund wall of tanks 52, 53, and 54. Under such a fire scenario, the emergency response process should be developed to protect the health of the staff and firefighters, facilities such as the piping systems and tanks, fuel in tanks, and the environment around the fuel storage tank farm. In the emergency response process, the mobilization, alert, and combat task types consisting of a series of functions are developed by referring to the

Table 1
The identified functions and their detailed description.

Task	Function	Input	Resource	Control	Precondition	Time	Output
Mobilization	F_1: Confirm location of fire	-	Alarm information	-	Well-performed monitoring system	As soon as possible	Fire information
	F_2: Contact the control room and shift officer for immediate action guidelines	F_1(O)	Radio/Telephone	Rescue rules and regulations	All relative officers stand by.	As soon as possible	Immediate action guidelines
	F_3: Actuate siren	F_2(O)	Alarm system	-	Well-performed warning systems	As soon as possible	Publication of information
Alert	F_4: Contact fire department	F_2(O)	Radio/Telephone	-	Fire department standing by.	As soon as possible	Successful connection with fire department
	F_5: Contact the fire marshal for instructions and actions	F_4(O)	Radio/Telephone	-	Fire marshal standing by.	As soon as possible	Specific action description
	F_6: Establish if any missing persons at assembly muster and advise fire officer	F_2(O)	Internet/Telephone	-	F_3(O)	As soon as possible	Confirming a person's status
	F_7: Establish incident command post and advise fire team leaders	F_5(O)	Internet/Telephone	-	All related departments standing by	As soon as possible	Incident command post
	F_8: Post the accident location and information	F_4(O)	Internet /Telephone	Principles of releasing accident information	-	As soon as possible	Publication of accident information
	F_9: Check extent of fire and escalation potential	F_7(O)	Experts with process experience and knowledge; Internet /Telephone	-	Information on fire, fuel, and facilities	As soon as possible	The fire risk evaluation results and prediction results
	F_{10}: Evaluate the availability of equipment and resources	F_7(O)	Experts with process experience and knowledge; Internet /Telephone	-	Information on equipment and resources	As soon as possible	The evaluation results on available equipment and resources
	F_{11}: Assess flame or heat affected facilities	F_7(O)	Experts with process experience and knowledge; Internet /Telephone	-	Information on fire, fuel, and facilities	As soon as possible	The evaluation results of facilities
	F_{12}: Develop response guidelines	F_6(O) F_9(O) F_{10}(O) F_{11}(O)	Experts with process experience and knowledge	Rescue rules and regulations	-	As soon as possible	Response guidelines
Combat	F_{13}: Sent technician to stand-by with equipment and resource	F_{12}(O)	Sufficient technician	-	-	As soon as possible	Technician standing by
	F_{14}: Isolate equipment and commence shutdown of affected and related facilities	F_{13}(O)	-	-	Information on equipment and facilities	As soon as possible	Successfully isolating and shutting down all equipment and facilities
	F_{15}: Pump the product of tanks 52, 53 and 54 to other tanks	F_{13}(O)	Pump facilities	Standard of pump operation	-	As soon as possible	Successfully transferring the product to another tank
	F_{16}: Respond to the incident area for shutdown supervision	F_{14}(O) F_{15}(O)	Technician	-	-	As soon as possible	Shutdown supervision in real-time
	F_{17}: Assemble the fire team with equipment and resource	F_{12}(O)	Firetruck; firefighter; PPE, SCBAS, etc.	-	-	As soon as possible	Successfully assembling enough SCBAS, PPE, firefighters, firetrucks, etc.
	F_{18}: All members don firefighting PPE, and SCBAS for firefighters in the hot zone	F_{17}(O)	F_{12}(O)	Standard of wearing firefighting PPE and SCBAS	-	As soon as possible	Firefighters wearing PPE and SCBAS
	F_{19}: Ensure all members don firefighting PPE	F_{18}(O)	F_{12}(O)	Standard of wearing firefighting PPE SCBAS	-	As soon as possible	Ensuring that firefighters wear PPE
	F_{20}: Direct fire team to inject foam to the bund wall under fire	F_{19}(O)	F_{12}(O) F_{17}(O)	Operation specifications of firetrucks	-	As soon as possible	Successfully extinguishing the fire
	F_{21}: Fire teams remain on standby until the area is declared safe	F_{20}(O)	F_{16}(O) F_{17}(O)	Standard of security	F_{19}(O)	As soon as possible	Safe storage tank area
	F_{22}: Monitor the response actions	F_{13}(O) F_{12}(O)	F_{14}(O) F_{15}(O) F_{18}(O) F_{19}(O) F_{20}(O) F_{21}(O)	-	-	As soon as possible	Monitoring information in real-time

emergency response plan developed by Baser and Behnam (2020). The identified functions and their detailed description are shown in Table 1.

In the design stage, each function is first characterized from six aspects, namely Input (I), Preconditions (P), Resources (R), Time (T), Control (C), and Output (O), which are shown in Table 1. It should be noted that it is unnecessary to describe all aspects of a function if they are not present in the system under examination. Then, A FRAM model is developed for the emergency response process, as shown in Fig. 7.

In the analysis stage, according to Section 3.3, the reliable emergency response process is the first-level performance index. According to the principles for main function type identification defined in Section 3.3, functions F_2, F_{12}, F_{14}, F_{15}, and F_{20} are defined as main function type. So, their performance variability is set as the second-level performance index. Specifically, functions F_2, and F_{12} in the mobilization and alert task types establish crucial connections with numerous functions in downstream task types. Functions F_{14}, $F_{15,}$ and F_{20} in the combat task type are directly related to the ultimate objective of the emergency response process. The others are defined as auxiliary function type and their performance variability is set as the third-level performance index.

In reference to the hierarchy of the performance index system outlined in Section 3.3, the analysis commences by evaluating the performance of the main function type.

(1) In the mobilization task type, the function F_2 promptly makes immediate action guidelines for the combat phase. The immediate action guidelines made by function F_2 are reliable because they consider the destroyed fire water network in the fuel storage tank farm and clarify a series of efficient functions to stop the fire from spreading, such as the plan to isolate equipment, shut down affected and related facilities, and pump the product to other tanks.
(2) In the alert task type, function F_{12} clarifies that the main aim of the combat task type is to extinguish the fire because the staff were able to escape in time, and no other facilities were destroyed by the earthquake. The function F_{12} develops a series of response action guidelines for firefighting. In addition, the guideline predicts that fire may not be extinguished within a specific time due to limited firefighters. However, damaged communication facilities and limited time make it unable to call more firefighters from the other organization. Therefore, the response guidelines are made based on currently available firefighters. However, response guidelines are sent to emergency responders a bit late.
(3) In the combat task type, F_{14} promptly and effectively isolates the other facilities from the fire and F_{15} promptly and effectively pumps the product of tanks 52, 53 and 54 to other tanks. However, in the function F_{20}, the firefighter may not be able to extinguish the fire in the bund wall of tanks 52, 53, and 54 within the specified time due to the coupling among these functions. The radiation may lead to the failure of Tank 63 and the fire may spread to Tank 63. In addition, the working hours of the firefighter exceed the specified time and they may receive injuries.

The performance of the functions F_{12} and F_{20} are negative. According to the coupling relationship shown in Fig. 7, all the relative functions can be identified, which are shown in Fig. 8. It should be noted that the performance of the functions F_2, F_{14}, and F_{15} is no longer analyzed due to their good performance. Then, the performance variability of each relative function is analyzed, and the negative performance variability is interpreted based on the functional resonance analysis. The analysis results are shown in Table 2.

The enhancement stage involves refining the emergency response planning based on the outcomes of performance variability analysis.

On one hand, suboptimal communication efficiency within F_5 introduces delays across various functions in the emergency response process, particularly along the coupling path. Notably, F_7 plays a crucial role in establishing the incident command post when F_5 provides instructions and actions. Given the high seismic Natech accident risk to fuel storage facilities, the prompt establishment of the incident command post is vital for formulating effective emergency response guidelines. Additionally, the one-way communication between the fuel storage tank farm and the fire department in F_5 signifies an information gap, potentially compromising the reliability of instructions and actions. Simultaneously updating seismic Natech accident-related information to both parties can enhance the efficiency of emergency response planning. Consequently, adjusting the cooperation model among these functions from a systemic perspective becomes essential.

On the other hand, the limited availability of firefighters responding to the seismic Natech accident poses a significant challenge. The widespread destruction caused by the earthquake necessitates deploying some firefighters to other affected areas for rescue operations and safeguarding key facilities and the environment. In this context, F_{12} develops response guidelines for F_{20} based on the constrained firefighter resources. However, F_{12} doesn't gather additional personnel from other organizations due to limited time and damaged communication facilities. While F_{20} takes appropriate measures as per the guidelines, the fire persists beyond the specified time due to inadequate firefighting resources. Moreover, the limited firefighters prove insufficient to handle potential Natech accidents triggered by aftershocks. Consequently, it

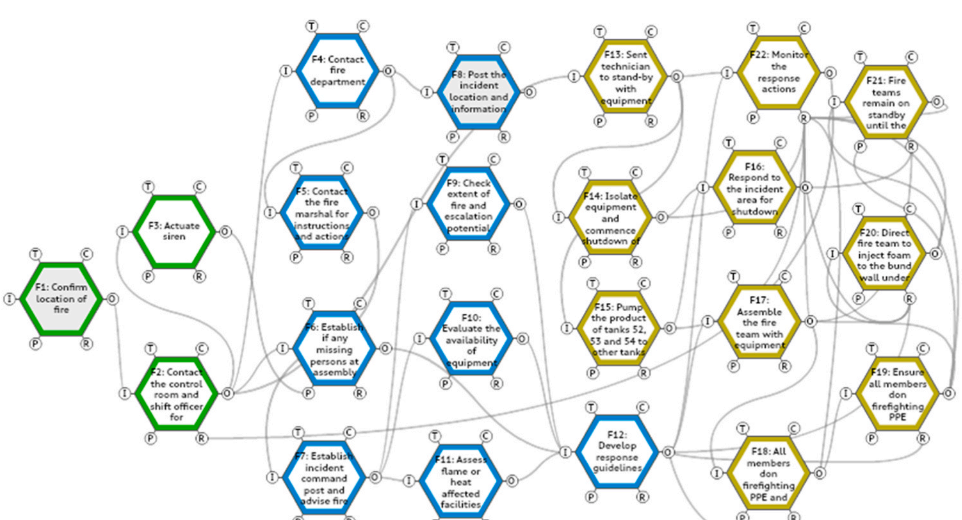

Fig. 7. The emergency response plan.

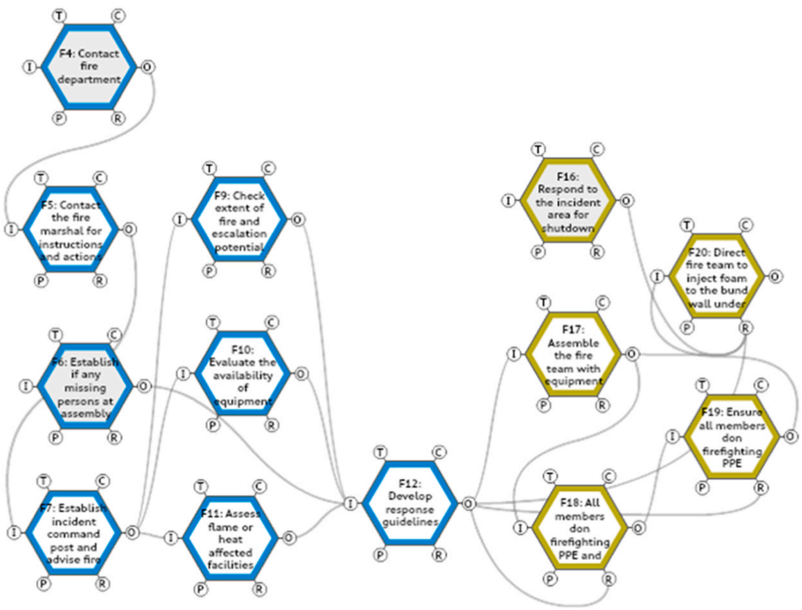

Fig. 8. The identified functions related to the negative performance of functions F_{12} and F_{20}.

becomes imperative to introduce additional functions focused on locating and mobilizing more firefighters for effective emergency response.

4.2.2. The second round of emergency response planning

In the understanding phase, functions are re-identified by considering the enhancement strategy developed in the last round of emergency response planning. As mentioned above, the fire in the bund wall of tanks 52, 53, and 54 cannot extinguished within the specified time. It results from the delay of a series of functions and the limited firefighter. As for the delay of a series of functions, it is essential to cancel the unnecessary functions F_5 (Contact the fire department for instructions and actions). As for limited firefighters, it is essential to establish bridges for communication with the other organizations and dispatch more firefighters from the other organizations, which are represented by $F`_1$ and $F`_2$. The other functions involved in the first round of the emergency response process are retained in the updated emergency response process.

In the design stage, all functions are characterized from six aspects, namely, Input (I), Preconditions (P), Resources (R), Time (T), Control (C), and Output (O). Although some functions in the updated emergency response process have been characterized in the last round of emergency response planning. It is essential to re-characterize some of these functions. For instance, the input of function F_7 in the original emergency response process is the function F_5. But the function F_5 is canceled in the updated emergency response process. Accordingly, the input of the function F_7 is served by the output of functions F_2 and F_4. In addition, the added functions are characterized by six aspects. To avoid duplication, we have omitted the description information of each function in this round. After characterizing the functions in the updated emergency response process, the FRAM is constructed, which is shown in Fig. 9.

In the analysis stage of the second round, the performance of the updated emergency response planning is analyzed by referring to the performance index system defined in Section 3.3. Similarly, the performance of the main functions F_{12}, and F_{20} is iteratively re-analyzed.

- The function F_{12} in the alert task type updates the response guideline on time. The response guideline explained the response actions from a systematic perspective to fight the fire in the combat phase. In addition, the response guideline directs the fire department to establish bridges for communication with other organizations and gather more firefighters. This guideline is reliable and is sent to emergency responders in time.
- Thanks to reliable response guidelines, more firefighters are sent to fight the fire in the bund wall of tanks 52, 53, and 54. The function F_{20} in the combat task type extinguishes the fire within an acceptable time. Each firefighter is well-protected during the process of extinguishing the fire.

As shown in the analysis stage, the main functions in the updated emergency response planning performed very well. Accordingly, the emergency response planning ends at this stage.

4.3. Discussion

A comprehensive case study, detailed in this section, is conducted to demonstrate the applicability and efficacy of the proposed method in emergency response planning which combines FRAM with a performance index strategy for a prioritization approach of main and auxiliary function type. The method is further scrutinized in comparison with the flowchart approach which is a traditionally utilized emergency response planning approach (Baser and Behnam, 2020; Zeng et al., 2022). To this end, the emergency response plan shown in Fig. 7 is redrawn in the form of a flowchart. However, the functions in the Fig. 7 are too many. To simply and clearly show the difference between the FRAM-based emergency response plan and the flowchart-based emergency response plan, we select the functions $F_{1–6}$ as examples for the comparison, as shown in Fig. 10.

As shown in Fig. 10, both FRAM and the flowchart employ visual representations involving boxes and arrows to convey emergency response planning. However, the latter lacks the level of detail and structure provided by the FRAM modeling approach. On the one hand, FRAM (Fig. 10(a)) meticulously defines hexagons (representing six aspects of a function), which contributes to the detailed description of functions and helps emergency responders to understand each function. In contrast, the description of each function in a flowchart (Fig. 10(b)) relies on the brainstorming of experts. On the other hand, the interconnecting lines in FRAM (Fig. 10(a)) can describe the detailed coupling relationships among functions. In contrast, the interconnecting lines in the flowchart (Fig. 10(b)) are mainly to describe the sequence of functions. As shown in Fig. 10, FRAM (Fig. 10(a)) let F_2 and F_3 serve as the

Table 2
The performance variability analysis of each function.

Function	Performance variability	Negative performance variability interpretation
F_{20}: Direct fire team to inject foam to the bund wall under fire	● Fire isn't extinguished within the specified time. ● The working hours of firefighters reach the limit.	In function F_{20}, firefighters inject foam to the bund wall under fire appropriately. But F_{17} doesn't gather enough firefighters and F_{12} delays the guideline issuing. Due to the coupling among these functions, the firefighters may not be able to extinguish the fire in the bund wall of tanks 52, 53, and 54 within the specified time. Fire may spread to the Tank 63 and damage the health of firefighters.
F_{19}: Ensure all members don firefighting PPE	● All members are well-wearing firefighting PPE. This is checked quickly and strictly	-
F_{18}: All members don firefighting PPE, SCBAS for firefighters in the hot zone	● All members don firefighting PPE, and SCBAS as required quickly.	-
F_{17}: Assemble the fire team with equipment and resource	● All available firefighters assemble on time although guidelines from F_{12} are delayed. ● F_{17} doesn't gather enough firefighters.	Although F_{17} is conducted according to guidelines from F_{12}. Guidelines just direct to gather currently available firefighters and fail to direct how to gather more firefighters.
F_{16}: Respond to the incident area for shutdown supervision	● All the facilities in the incident area are shut down in time and supervised effectively.	-
F_{12}: Develop response guidelines	● The response guideline gives a full description of each action. ● The guideline predicts that fire may not be extinguished within a specific time due to limited firefighters. But it took no action for this situation. ● F_{12} issues the guideline a little late.	F_{12} designs guidelines as soon as possible and F_6 issues the evaluation information on time. But F_{11}, F_{10}, F_9 issues the evaluation information a little late. Facing limited time and damaged communication facilities, F_{12} doesn't call more firefighters from the other organizations.
F_{11}: Assess flame or heat affected facilities	● The assessment results are reliable. ● F_{11} issues the assessment results a little late.	F_{11} conducts the assessment as soon as possible. But the command from Function F_7 is delayed.
F_{10}: Evaluate the availability of equipment and resources	● The assessment results are reliable. It revealed inadequate firefighters ● F_{10} issues the assessment results a little late.	F_{10} conducts the assessment as soon as possible. But the command from Function F_7 is delayed.
F_9: Check extent of fire and escalation potential	● The assessment results are reliable. ● F_9 issues the assessment results a little late.	F_{14} checks the situation as soon as possible. But the command from Function F_7 is delayed.
F_7: Establish incident command post and advise fire team leaders	● The command post clarifies all aspects that should be evaluated. The advice is reliable and is described clearly. ● The incident command post is established a bit late. And The advice is issued a little late.	The incident command post is established when F_5 gives instructions. But instructions and actions from Function F_5 are delayed.
F_6: Establish if any missing persons at assembly muster and advise fire officer	● All the people escape on time. This information is clear and reliable. ● F_6 issues the information on time	-
F_5: Contact the fire department for instructions and actions	● In Function F_5, communication efficiency is low.	F_4 notifies the fire department in time. However, the one-way communication between staff and the fire department in F_5 results in low communication efficiency.
F_4: Notify fire department	● F_4 notifies the fire department in time.	-

input and the precondition of F_6, while the flowchart (Fig. 10(b)) let both F_2 and F_3 serve as the input of F_6. Compared to FRAM, the flowchart is incapable of describing the difference between F_2 and F_3. FRAM can show that F_2 gives a check order to F_6 and it is essential to let everyone hear the alarm (F_3) before identifying whether there are missing persons (F_6). Therefore, FRAM can furnish a more comprehensive and detailed description of the emergency response process and planning. Moreover, FRAM adopts a systematic perspective, illustrating different phenotypes of each function's output. Consequently, the proposed FRAM-based approach effectively guides stakeholders in understanding, designing, analyzing, and enhancing the emergency response process, taking into account the specific characteristics of a Natech accident.

In addition, the vulnerability of the emergency response process to changing work conditions necessitates a dynamic adaptation to variable circumstances. While flowchart-based methods typically construct emergency response plans based on predetermined work conditions, the proposed FRAM-based method introduces a continuous improvement cycle, encompassing understanding, designing, analyzing, and enhancing the emergency response process. This iterative approach facilitates continuous analysis and improvement of the emergency response process performance during a Natech accident. Despite its advantages, the application of the proposed approach presents several challenges.

First, in Natech accidents within the chemical industry, which can impact facilities, the environment, and human health over a broad area, the emergency response process comprises numerous coupled functions, resulting in a complex FRAM model that may pose challenges for responders. To mitigate this complexity, visualization enhancements through software can be employed to clarify the FRAM models and interpret functions and their relationships.

Second, the effectiveness of the proposed emergency response planning method relies on extensive data, encompassing characteristics, coupling relationships, performance variability of functions, Natech accident details, and emergency response resources. Gathering, comprehending, and analyzing such heterogeneous data from multiple sources within a limited timeframe is critical but poses a substantial challenge. Research on big data technologies is imperative to enhance the efficiency of emergency response planning.

Finally, in Natech accidents, emergency response resources are typically limited. Although the proposed method allows approximate adjustments to address dynamic Natech conditions, predicting the dynamic evolution of a Natech accident is crucial for the judicious allocation of limited emergency response resources. Machine learning emerges as a promising avenue for predicting the dynamic evolution of Natech accidents based on historical data from similar incidents. The integration of Machine Learning and FRAM applications as the FRAM Model Visaulizer (FMV) are currently missing.

5. Conclusion

This paper presents a FRAM-based approach for emergency response planning in Natech accidents, comprising four sequential stages: understanding, designing, analyzing, and enhancing the emergency

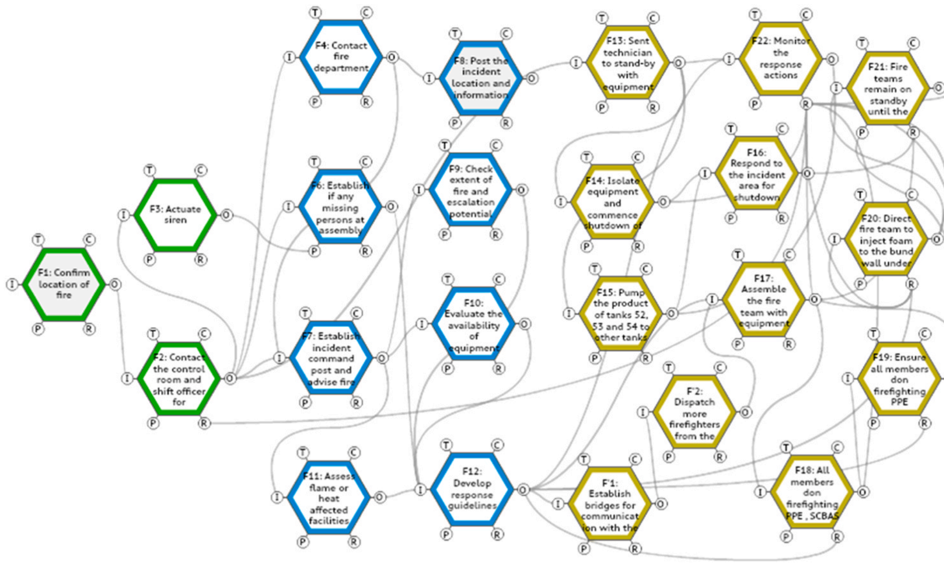

Fig. 9. The updated emergency response plan.

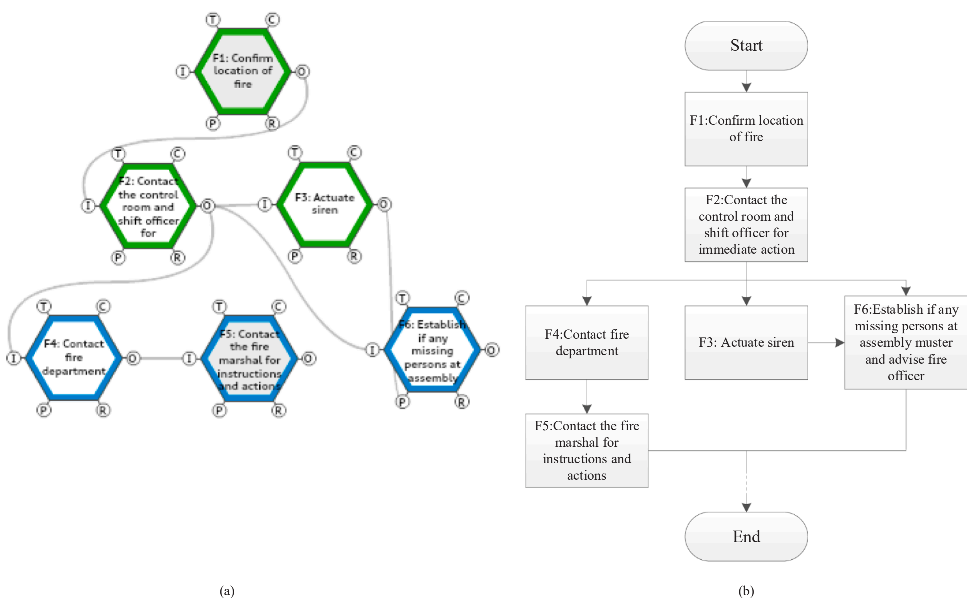

Fig. 10. Comparison between the FRAM-based and flowchart-based emergency response plan.

response process. In the initial understanding stage, we systematically identify all functions relevant to protecting human health, the environment, and facilities within the emergency response process. Moving to the designing stage, a detailed description of all functions and their coupling relationships is provided, leading to the construction of a comprehensive FRAM model for the emergency response process. The third stage involves analyzing the emergency response process, and establishing a hierarchy of a performance index system to assess individual function performance. Identification and interpretation of negative performances contribute to an enhanced overall understanding. In the final stage of enhancing the emergency response process, strategies for managing performance variability are developed from a functional and systematic perspective. This holistic approach facilitates the continual improvement of the emergency response process during a Natech accident, forming a cyclical process for ongoing refinement and optimization.

To illustrate the method's effectiveness, we conduct a case study for emergency response planning in a seismic Natech accident within a fuel storage tank farm. The case study highlights the advantages of the proposed method in portraying the functions of the emergency response process and their relationships in detail and directing how to enhance the emergency response process constantly during its operation. This demonstrates its utility in emergency response planning and providing insights into the characteristic performance of the process from a systematic perspective.

Despite its merits, the application of the proposed method presents challenges, including handling large volumes of diverse data, predicting the dynamic evolution of Natech accidents, and highlighting the time-dependent and strong coupling characteristics inherent in the evolution of Natech accidents. Addressing these challenges is crucial for the successful implementation of the proposed FRAM-based approach in emergency response planning. To this end, the proposed method will be enhanced from three aspects in further studies.

- It will be of great significance to explore and incorporate more sophisticated time-dependent modeling techniques that can more accurately capture the evolution of Natech accidents over time. This may involve the use of dynamic simulation models or the integration of temporal data analysis methods to track and predict the progression of events and their impacts.

- To address the strong coupling characteristics of Natech accidents, the proposed method will be refined by including a more detailed analysis of interdependencies and interactions between different components and systems affected by Natech accidents. This could involve the development of network analysis methods, or the application of systems dynamics approaches to better understand and represent these complex relationships.
- The evolution of Natech accidents over time may lead to the goal adjustment of the emergency response plan. Means-end analysis supports the iterative refinement of the emergency response plan by continually reassessing goals and means in light of new information or changing circumstances related to the Natech accident. Therefore, further studies will focus on utilizing the Means-end analysis to direct the adapting and fine-tuning of FRAM to better reflect how the emergency response plan adapts to the evolution of Natech accidents.

CRediT authorship contribution statement

Weizhong Wang: Writing – review & editing. **Arie Adriaensen:** Validation, Writing – review & editing. **Xinwang Liu:** Project administration, Resources, Supervision, Writing – review & editing. **Ming Yang:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Qiaohong Zheng:** Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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