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Research article

Analysis of potential fire and explosion incidents in an LNG terminal in a port area using the FRAM method

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Abstract

The commercialization of liquefied natural gas (LNG) offers significant benefits to various industries; however, its chemical properties pose substantial risks, potentially resulting in catastrophic incidents. The transportation, storage, and utilization of flammable substances like LNG can lead to industrial accidents, such as fires and explosions, if not adequately controlled. To mitigate these risks, conducting a comprehensive hazard and risk analysis at the worksite and implementing appropriate safety measures are essential. This study focuses on analyzing potential fire and explosion scenarios that may arise in a port area engaged in LNG operations, employing the Functional Resonance Analysis Method (FRAM). Accident processes are examined through functional analysis, identifying 20 distinct functions. Of these, 7 functions were categorized as high risk, 5 as medium risk, and 8 as low risk. Based on the findings, this study provides recommendations for safety measures aimed at safeguarding both occupational health and environmental integrity.

Keywords: *Explosion; FRAM; liquefied natural gas; safety measures; occupational health and safety*

1. Introduction

The global energy demand continues to grow as it plays a crucial role in enhancing the well-being of populations worldwide. Among the various energy sources available, fuel oil and natural gas have been preferred choices, particularly since the 20th century Natural gas is recognized as one of the cleanest fossil fuels due to its high hydrogen-to-carbon ratio and low sulfur content, provided it is commercialized (Wu et al., 2023). Its composition includes gases such as methane, ethane, butane, propane, carbon dioxide, oxygen, and nitrogen, with methane being the primary component (Akpinar and Basibuyuk, 2011).

Due to the uneven distribution of natural gas production, transportation over long distances are essential. For this purpose, natural gas must be converted into a liquefied form (liquefied natural gas-LNG) at -162°C and atmospheric pressure. In its liquefied state, natural gas occupies 1/625th of its original volume and has a density of approximately 45%, making it suitable for long-distance transport and storage in commercial seaports via sea transportation (Avci et al., 1995; Shirazi et al., 2019). The increasing utilization for commercial purposes has led to a growing demand for this energy resource in recent years

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(Pospisil et al., 2019). According to data from the International Energy Agency, the rising LNG demand in Asian countries has contributed significantly to overall market growth (Akpinar and Basibuyuk, 2011).

From an environmental perspective, the use of LNG as a fuel offers a promising solution to reducing emissions. To accommodate the growing demand, high-capacity tanks (160,000 m^3 and above) have been developed to store LNG reserves. However, despite the advantages LNG offers to various industries, its chemical properties pose significant risks, potentially leading to catastrophic incidents (Baalisampang et al., 2019). Methane, the primary component of LNG, can detonate when it forms a gaseous mixture with air at concentrations of 5-15%. Loss of control during the transportation, storage, or utilization of LNG could result in severe accidents, including fires and explosions (Animah and Shafiee, 2020).

Particularly, LNG stored in tanks can evaporate and form explosive vapors in the event of a leak. Historical analyses of explosion disasters have identified LNG vapor leaks as a frequent cause of such incidents. To mitigate the risks of fires and explosions in workplaces handling LNG, hazard and risk analyses must be conducted, and appropriate safety measures should be implemented (Animah and Shafiee, 2020; Huffman et al., 2024).

Risk assessment, a relatively young scientific discipline developed 30-40 years ago, is widely applied across various industries, including healthcare, engineering, infrastructure, transportation, security, defense, and the social and legal sectors (Aven, 2016). While traditional risk analysis methods focus on investigating the direct consequences of accidents, modern methods such as the Functional Resonance Analysis Method (FRAM) and Systems-Theoretical Accident Modeling and Processes (STAMP) have gained prominence. These approaches aim to analyze the complex nature of accidents and understand how seemingly normal operations can lead to accidents (Patriarca et al., 2020; De Carvalho, 2011).

FRAM examines how a system operates as a whole, identifies potential disruptions in its functionality, and determines ways to enhance flexibility in response to such disruptions. Unlike traditional methods, FRAM focuses on system-level interactions rather than the direct outcomes of accidents (Bal Besikci and Sihmantepe, 2020). Initially, FRAM was applied in the aviation sector to investigate accidents and has since been adopted across various industrial domains (Patriarca et al., 2017).

In this study, a scenario involving a potential fire and explosion in an LNG tank located in a designated shipyard area was developed, and the hazards and risks were analyzed using the FRAM method. This approach enabled the identification of all potential hazards, risks, and related variable factors as an integrated system. The relationships between seemingly independent events were also examined. The findings will be presented using the FRAM model to provide a comprehensive understanding of the system's vulnerabilities and potential disruptions.

2. Materials and methods

2.1. Functional resonance analysis method (FRAM)

FRAM analysis, which is used to create potential accident scenarios that may occur in work environments, was introduced by Hollnagel (2016) and developed in the following years (Hollnagel, 2016). FRAM is a systemic analysis method that tries to explain the non-linear relationships and interactions between different functions in a system. FRAM focuses more on the explanation of complex interactions in the system. By analyzing the activities of a normal system, it takes into account functional variables and disturbances between variables (Naeini and Nadeau, 2022). The functions in a planned system, scenario, or simulation are defined functionally, and by characterizing each variable in the determined functions, it enables the interpretation of the interactions between them and the provision of recommendations for taking the necessary safety measures in case of the emergence of an unexpected variable (Furniss et al., 2016). The goal of FRAM analysis is to find out how the components of the functions affect the events and how the results will change with the changing conditions. FRAM is an analysis method that requires the use of imagination. It considers the system as a whole, not in parts, and provides the person who does it with a clue, not an answer (Franca et al., 2021). The main purpose of FRAM analysis is to find the connections between the variables of the function and to examine the system function by analyzing how they affect the system. FRAM is a new risk analysis method and therefore it is a long and difficult analysis method to prepare. The main steps of FRAM analysis are;

- Determine the main goal of the model and define the event to be analyzed,
- Determine and characterize the main functions of the process according to input, output, preconditions, resources, time and control,
- Characterize the actual/potential variability of the functions,
- Identify functional resonances based on potential connections between functions, considering both normal and worst-case variability,
- Provide ways to monitor and minimize performance variability (Hollnagel, 2012).

The Functional Resonance Analysis Method is based on four basic principles: the basic principle of success and failure, the principle of approximate adjustments, the principle of emergence, and the principle of functional resonance. FRAM analysis takes place in four main stages (Hollnagel et al., 2014; Koruklu and Ozay, 2021).

- Defining functions
- Determine variability
- Bringing variability together
- Managing variability

The first stage of FRAM analysis is to create the functions and determine the parameters of the functions. In FRAM analysis, functions provide the connection between each other. A function can have six parameters. Not all these parameters have to be in a function (Rosa et al., 2015).

Function Parameters;

- Input (I)
- Output (O)
- Control (C)
- Time (T)
- Source (S)

- Prerequisite (P)

For each function determined in the risk analysis, the parameters in Fig. 1 are created and a connection is established between the determined functions. In the FRAM analysis, each function can be connected to a single module or a connection can be established on more than one module. In the FRAM analysis, the common performance value that reveals the factors affecting the system and how the system operation is affected is revealed. In this context, the common performance value is classified as sufficient, insufficient, and unpredictable. Common performance evaluation criteria are given in Table 1.

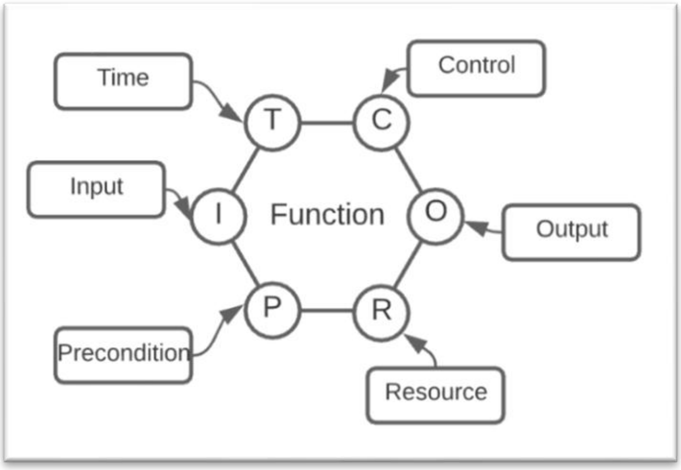

Fig. 1. Function parameters.

Table 1
FRAM common performance evaluation criteria.

Common Performance Value	Probability of Risk Occurrence
Adequate	Very Low
Inadequate	High
Unpredictable	Very High

The changes that may occur between the specified functions and performance values are divided into 4 categories. These categories explain the fluctuations that occur between the functions and performance values. The performance-based changes in the specified functions are evaluated in 4 categories and are given in Table 2.

Table 2
Performance-based change.

Performance Based Fluctuations	Common Performance Value
Random Functional Module	Unpredictable≥3 or Inadequate≥8
Opportunity Functional Module	Unpredictable=2 or Inadequate≥6
Tactical Functional Module	Unpredictable=1 or Inadequate≥4
Strategy Functional Module	Unpredictable=0 or Inadequate≤3

The categories in Table 2 describe the fluctuations in the determined functions. The random functional module in these categories is the module with the largest fluctuations, and the random evaluation of one of the determined functions explains why the error occurs very easily and creates functional resonance (Ozsayan and Barlas, 2023). While creating the FRAM analysis, the FRAM Model Visualizer (FMV) software tool introduced by Hill and Hollnagel (2016) is used. The determined functions are entered into the software system with the FRAM analysis stages and the connection between the functions is created (Hill and Slater, 2024). Fig. 2 shows an example of FRAM obtained from the software system.

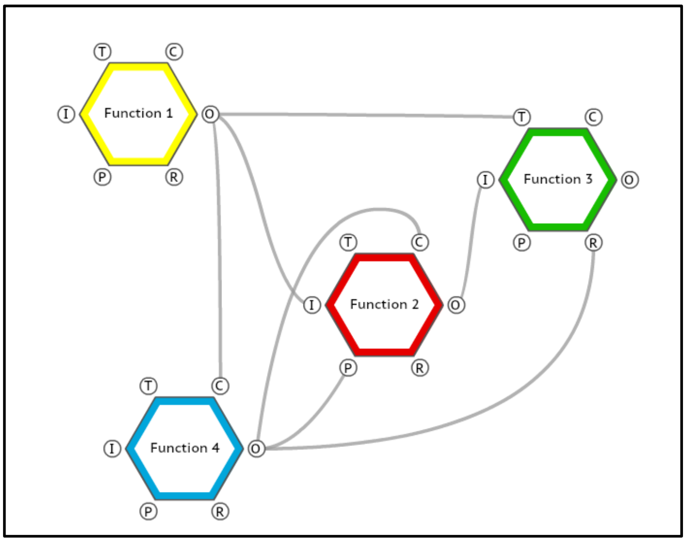

Fig. 2. FRAM connection example.

In this study, a port area located in the Marmara Region of Turkey and having an LNG terminal was determined. This area is an important area in terms of maritime transportation and employment and approximately 150,000 people are employed. The location of the LNG tank in the area is given in Fig. 3.

Fig. 3. Port area location.

A case study was conducted on occupational health and safety regarding a possible fire and explosion in an LNG tank used for commercial purposes. This analysis aimed to adopt proactive approaches in the field of occupational health and safety, to combat risks at source by detecting possible hazards in advance and to take necessary precautions to increase the health and safety of employees, and in this context, a possible fire and explosion in an LNG tank was analyzed using the FRAM analysis method. Before starting the FRAM analysis, a scenario was prepared for the possible fire and explosion process.

2.2. Scenario

While storing 40,000 m3 of LNG for commercial use on a chemical tanker ship at the LNG terminal in the Marmara Region, an LNG leak occurred due to an unnoticed and invisible crack in the tanker supply pipeline. The leak continued because the gas detectors on the ship did not activate and the LNG, which had turned from liquid to gas, began to accumulate in a closed area. Methane, which turned into gas and is an important component of LNG, began to form an explosive vapor cloud.

Table 3
Functions and variables related to functions.

	Function	FD	Variable	Description
F1	LNG tanker vessel leaks due to crack in supply pipeline	F1D1	The leak was detected early.	The risk of fire or explosion due to leakage has been eliminated.
		F1D2	The leak went unnoticed.	Explosion and fire occurred due to the methane gas in the leaking LNG reaching the explosion percentage.
F2	The gas detector on board failed to activate and the leaking LNG entered the gas phase, creating a flammable gas cloud	F2D1	The flammable gas cloud intervened before it reached the explosion percentage	The methane in LNG was intervened before it reached the explosion percentage, thus eliminating the risk of explosion and fire.
		F2D2	The flammable gas cloud could not be intervened.	Explosion and fire occurred due to the methane in LNG reaching the explosion percentage.
F3	An explosion occurred on the ship when the methane in the flammable gas cloud reached the explosion percentage.	F3D1	It happened during the day.	The shipyard has many employees.
		F3D2	It happened at night.	At the shipyard, there are only shift workers and those on duty for the transfer process.
		F3D3	There was a small explosion.	It only requires intervention to the LNG tanker and the workers on board.
		F3D4	There was a very violent explosion.	It requires immediate intervention to the LNG tanker vessel being worked on, the surrounding vessels and the workers on board.
		F3D5	Temperature high	The risk of a post-explosion fire is increased and the environment in which it can impact is larger.
		F3D6	Temperature low	The risk of fire occurring after the explosion has decreased and the environment it will affect is limited.
F4	The explosion released methane gas into the environment.	F4D1	Low impact on workers and the environment.	No emergency intervention required for workers and the environment.
		F4D2	Highly impacted employees and the environment.	Immediate intervention is required for workers and the environment.
F5	Fire caused by explosion	F5D1	The fire is under control.	The fire was prevented from growing. Measures were taken to minimize the impact on people and the environment.
		F5D2	The fire grew.	The fire could not be brought under control. People and the environment have been greatly affected. Because of this impact, people and the environment need urgent intervention.
F6	Safety valve on tanker vessel activated	F6D1	The safety valve activated without any problems.	That is what is necessary.
		F6D2	The safety valve failed to activate.	It was activated manually.
F7	The electrical system has been disabled.	F7D1	The electrical system was automatically deactivated.	That is what is necessary.
		F7D2	The electrical system could not be deactivated.	The system was manually deactivated.
F8	An emergency alert was issued at the shipyard.	F8D1	Emergency alert has been issued.	People in the area were informed of the emergency. Early precautions were also taken in the neighborhood.
		F8D2	The emergency alarm didn't work.	People in the area could not be informed about the emergency. Early measures could not be taken due to the lack of information about the situation.
F9	The shipyard's emergency response team arrived at the scene.	F9D1	Emergency teams arrived on the scene just in time.	Emergency intervention happens just in time.
		F9D2	Emergency crews did not arrive on the scene in time.	Intervention is disrupted.
F10	Employees were directed to assembly areas for evacuation.	F10D1	The emergency plan was adhered to and the area was quickly evacuated.	Evacuation and intervention happen just in time.
		F10D2	There was chaos because the employees panicked.	Evacuation is delayed, exposing workers to another explosion and more toxic gases.
F11	Entrances and exits to the scene were closed.	F11D1	Entrances and exits were closed after checking that no one was left at the scene.	That is what is necessary.
		F11D2	The entrances and exits were closed, but due to lack of control, some people remained at the scene.	The scene is checked again. Workers remaining in the area will continue to be exposed to the explosion and toxic gases.
F12	The injured were treated at the scene.	F12D1	Those injured at the scene were treated just in time.	The injured received first aid on time and were transferred to ambulances on time.
		F12D2	Response to the injured at the scene was delayed.	The first aid and ambulance transport of the injured was not timely. Their condition deteriorated.
F13	Emergency responders were called.	F13D1	Emergency responders were notified just in time.	The explosion and fire were intervened from the sea at the right time.
		F13D2	Emergency responders were notified late.	Response to the explosion and fire from the sea was delayed. The time to bring the situation under control has increased.

F14	General control was carried out in the bay with boats by the teams.	F14D1	The controls were carried out correctly.	That is what is necessary.
		F14D2	Checks detected deficiencies.	Areas not checked by the teams could not be intervened. Checks are carried out again and completely.
		F14D3	While the controls were taking place, the boats malfunctioned, and the controls were interrupted.	An emergency response team is called to the boats and the team that will provide controls is sent to the place of the malfunctioning boat.
F15	The teams started to intervene with the necessary equipment to prevent the spread.	F15D1	The intervention was timely and correct.	The incident was contained.
		F15D2	During the intervention, a malfunction occurred, and the intervention could not be carried out.	The incident grew and there was an increase in the number of people affected. A team was dispatched to fix the fault early.
F16	They made sure the incident was under control.	F16D1	The situation is under control.	That is what is necessary.
		F16D2	The situation could not be contained.	The incident has escalated and there has been an increase in those affected. The scene has been asked to be checked again.
F17	Cooling work has begun.	F17D1	The cooling works were successfully realized.	The environment has been adapted to eliminate the risk of explosion and fire recurrence.
		F17D2	The cooling work could not be carried out in a complete and timely manner.	The environment could not be made safe. There is a risk of explosion and fire recurrence.
F18	Debris removal has begun.	F18D1	Debris removal was carried out safely.	Hazards such as falling and being trapped under the material were eliminated and a new accident was prevented.
		F18D2	Debris removal could not be carried out safely.	An accident occurred while debris was being removed. Teams were deployed to ensure ambient safety.
F19	Cleanup operations have started for the LNG leaking into the sea.	F19D1	LNG cleaning operations were carried out thoroughly and accurately.	The danger of methane gas for marine life and the atmosphere has been eliminated.
		F19D2	LNG cleaning operations could not be carried out.	Methane gas is dangerous for living things and the environment. Methane gas should be measured in the environment and cleanup should be carried out completely and correctly as soon as possible.
F20	Damage assessment work has begun.	F20D1	The team started damage assessment on time.	Timely loss assessment for the enterprise is important for economy and sustainability.
		F20D2	The team was late in starting the damage assessment.	Delays in damage assessment have a negative impact on the economy and sustainability. Damage assessment should be carried out as soon as possible.

The explosive vapor cloud formed in the region reached 5%-15% degrees and caused an explosion in the terminal. The explosion that could have occurred according to the scenario created was analyzed with FRAM and explained in the findings section.

3. Results

Functions were determined for the hazards and risks that may arise by analyzing the possible explosion of the LNG tank in the shipyard port area by the FRAM analysis method. The functions are indicated with the letter "F" and the parameters that should occur for each function are explained and given in Table 3.

The parameters of the functions are determined separately for each function in Table 3. After the parameters of the functions were determined, the next step was to determine the variables. Variables were determined for each function and the variables were numbered with the letter D and explanations were made including the actions to be taken regarding the determined variables.

Within the scope of the analysis, 20 functions were defined and the impact of each function on security was evaluated. In this analysis, the functions were classified according to their risk levels; %35 (n=7) of them were determined as high risk, %25 (n=5) as medium risk and %40 (n=8) as low risk and are given in Fig. 4.

As a result of the analysis, the functions were examined one by one, and it was seen that the function coded F3 "An explosion occurred on the ship when the methane in the flammable gas cloud reached the explosion percentage" was the strongest function in the analysis. A visual analysis of the function is given in Fig. 5. This function is explained below to provide an example of how the result of the analysis is interpreted.

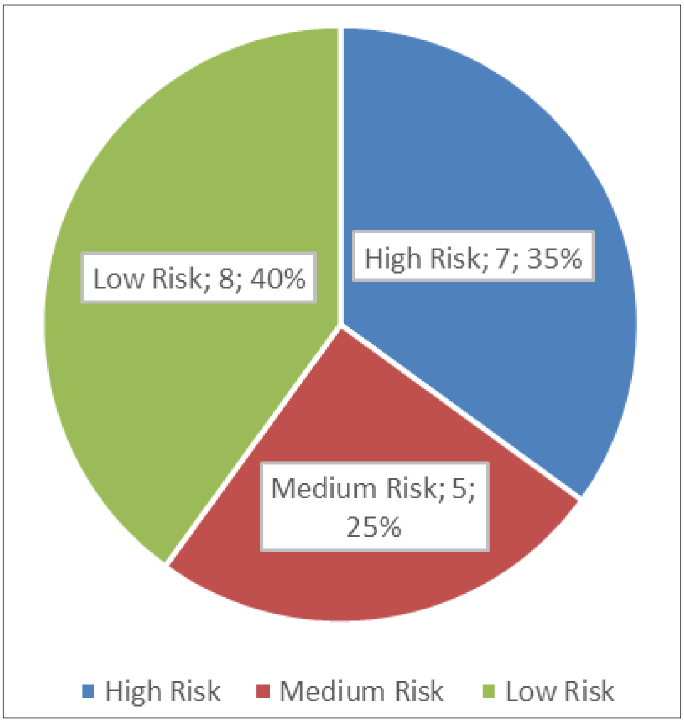

Fig. 4. Risk levels.

The F3 function has 2 inputs: "F1- A leak occurred due to a crack in the supply pipeline on the LNG tanker ship", "F2- The

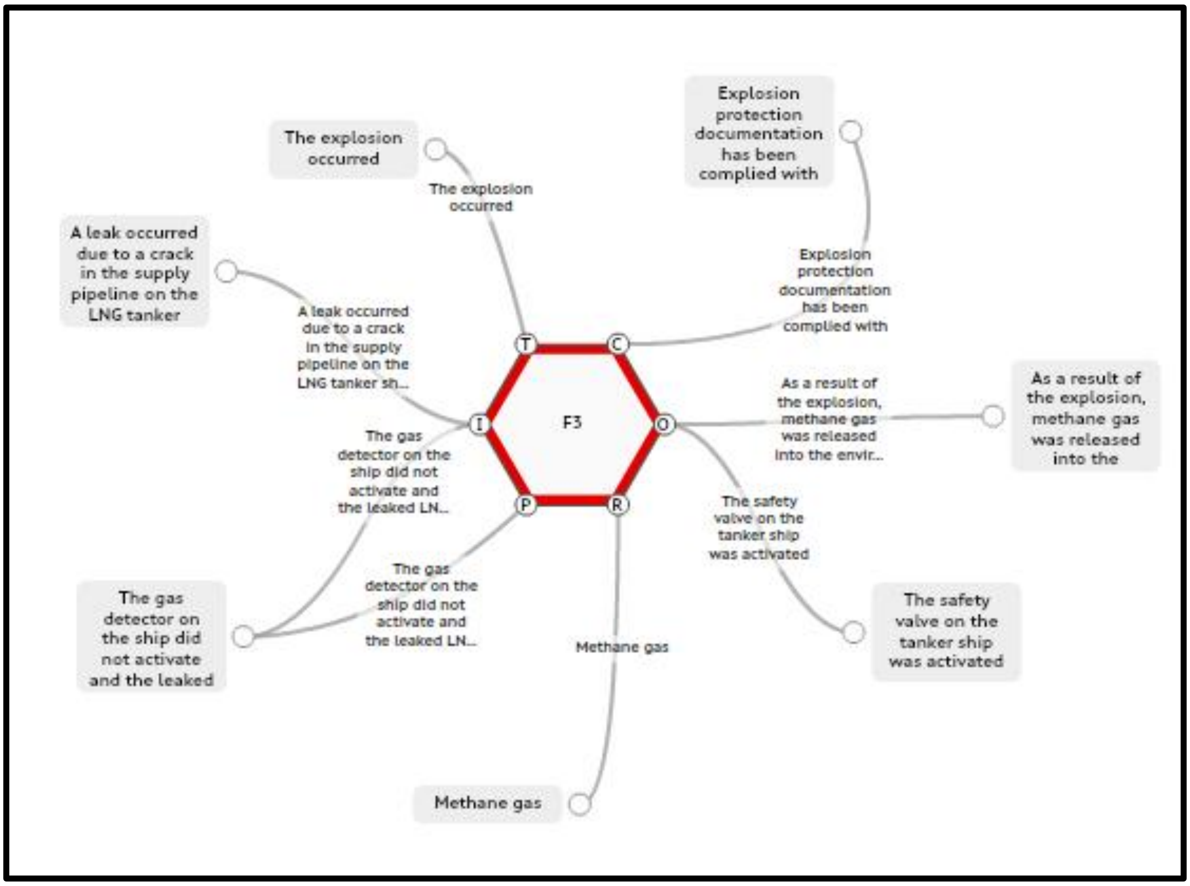

Fig. 5. Analysis image of F3 function.

gas detector on the ship did not activate and the leaked LNG passed into the gas phase and formed a flammable gas cloud”, 3 outputs: “F4- Methane gas was released into the environment as a result of the explosion”, “F5- A fire occurred as a result of the explosion”, “F6- The safety valve on the tanker ship was activated”, 1 precondition as “F2- The gas detector on the ship did not activate and the leaked LNG passed into the gas phase and formed a flammable gas cloud”, 1 source as “Methane gas”, 1 control as “Explosion protection document was complied with” and 1-time parameter as “Explosion occurred”.

The function F3 can have 6 variables. F3D1- May occur during the day. Since there will be a lot of human circulation (current employees, daily subcontractors, guests, deliverers) during working hours in the shipyard during the daytime and due to the intensity of hazardous work, the number of people affected by an explosion that may occur will be high. This situation will affect the response time and evacuation operations of the emergency teams in the shipyards “F9, F10, F12, and F15”.

F3D2- It may occur at night. According to this variable, the number of people affected by the explosion that may occur will be at a minimum level since the human circulation (night shift workers and transfer workers) and the intensity of dangerous work will decrease. However, toxic smoke from explosions and fires may affect people in the immediate vicinity. The precautions and interventions to be taken should be planned by considering these situations.

F3D3- Explosion may be of low intensity. People outside the transfer area may be moderately affected by the explosion. The damage that may occur because of the explosion is at a level that will not harm the business. Necessary evacuation and emergency response methods should be planned as employees located close to the LNG tanker will be affected.

F3D4- The explosion may be very violent. Since people in both the transfer area and other work areas can feel the explosion violently, it may cause panic. In this case, it is of great importance that an effective intervention plan is immediately put into effect to prevent the effect from growing and to manage the crisis correctly. People and employees in the vicinity should be taken to the assembly area quickly and safely. Effective and correct intervention should be carried out for people and the environment affected by the methane gas formed as a result of the explosion that may occur. Emergency intervention is required for the LNG tanker ship in question, the surrounding ships, and the employees there. The area of activity is greatly damaged and therefore the customer who makes the operation and investment suffers economic losses. This variability will be applied to the “F4, F5, F6, F7, F8, F9, F10, F11, F12, F13, F14, F15, F16, F17, F18, F19, F20” functions.

Therefore, variations in the F3 function may affect “F4, F5, F6, F7, F8, F9, F10, F11, F12, F13, F14, F15, F16, F17, F18, F19, F20” functions, may cause changes in intervention methods or may require the addition of new functions.

F3D5- Temperature may be high. The risk of fire after the explosion has increased and the area that the fire can affect is growing. Fire extinguishers must be in the correct position and ready for use to intervene in time for the fire that may occur. The intervention should be started by the fire extinguishing team determined in the shipyard. If the team is insufficient, the fire brigade should be called urgently.

F3D6- The temperature may be low. The risk of fire following the explosion is reduced and the area that the fire can affect remains limited. Attention should be paid to the risk of fire spread due to wind. Fire extinguishers must be in the correct position and ready for use in order to be able to intervene in time for the fire that may occur. It should be intervened by the fire extinguishing team determined in the shipyard.

Fig. 6 shows the areas that may be affected as a result of a possible explosion in the shipyard area.

The red area is the first area to be affected when the explosion occurs and is the area where the hazard severity will be seen at the highest level. It is important to take appropriate safety measures for this area. The areas shown in yellow color are the areas where the hazard level will be seen at a high level, although they are of medium risk. Green areas are the areas where the effects of the explosion will be less than the red and yellow areas.

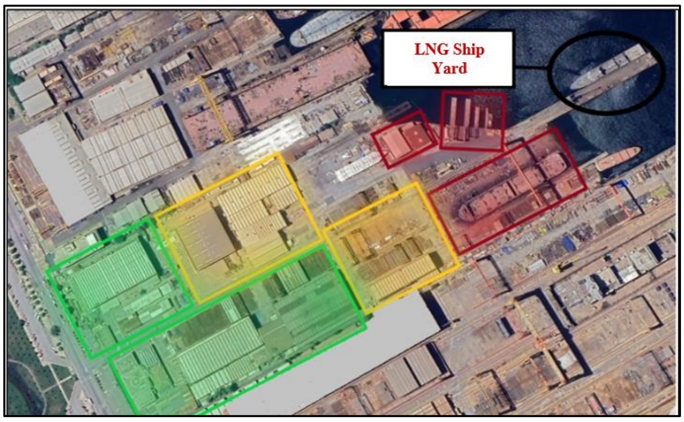

Fig. 6. Areas to be affected by the explosion.

In the next stage of the FRAM method, the relationship between the parameters determined for the functions was analyzed. The visual output of the analysis resulting from the analysis is shown in Fig. 7. In the FRAM visual, it is seen how the parameters affect each other and how a parameter can be the parameter of many functions.

4. Discussion

According to the *Regulation on Workplace Hazard Classes Regarding Occupational Health and Safety*, which came into effect in Türkiye in 2012, commercial LNG storage activities are classified as “very hazardous workplaces” due to their critical implications for occupational health and safety. Increasingly, scientific studies are being conducted to assess the potential explosion and fire risks associated with the oil and gas industry (Ma and Huang, 2019).

This study aims to conduct a risk analysis using the Functional Resonance Analysis Method (FRAM) to evaluate potential explosion and fire hazards in an LNG tanker within a designated shipyard port area. The study focuses on identifying the functions and variability parameters associated with these hazards and examining the relationships between them. A process comprising 20 functions was defined for the explosion scenario involving an LNG tank leak in the shipyard.

Three functions were identified as particularly critical, representing high accident risk in LNG tanker operations:

F1: A leak occurred due to a crack in the supply pipeline of the LNG tanker.

F2: The gas detector on the ship failed to activate, allowing the leaked LNG to vaporize and form a flammable gas cloud.

F3: An explosion occurred when the methane in the flammable gas cloud reached its explosive concentration.

Other functions identified were associated with processes occurring after the explosion event. The analysis revealed that

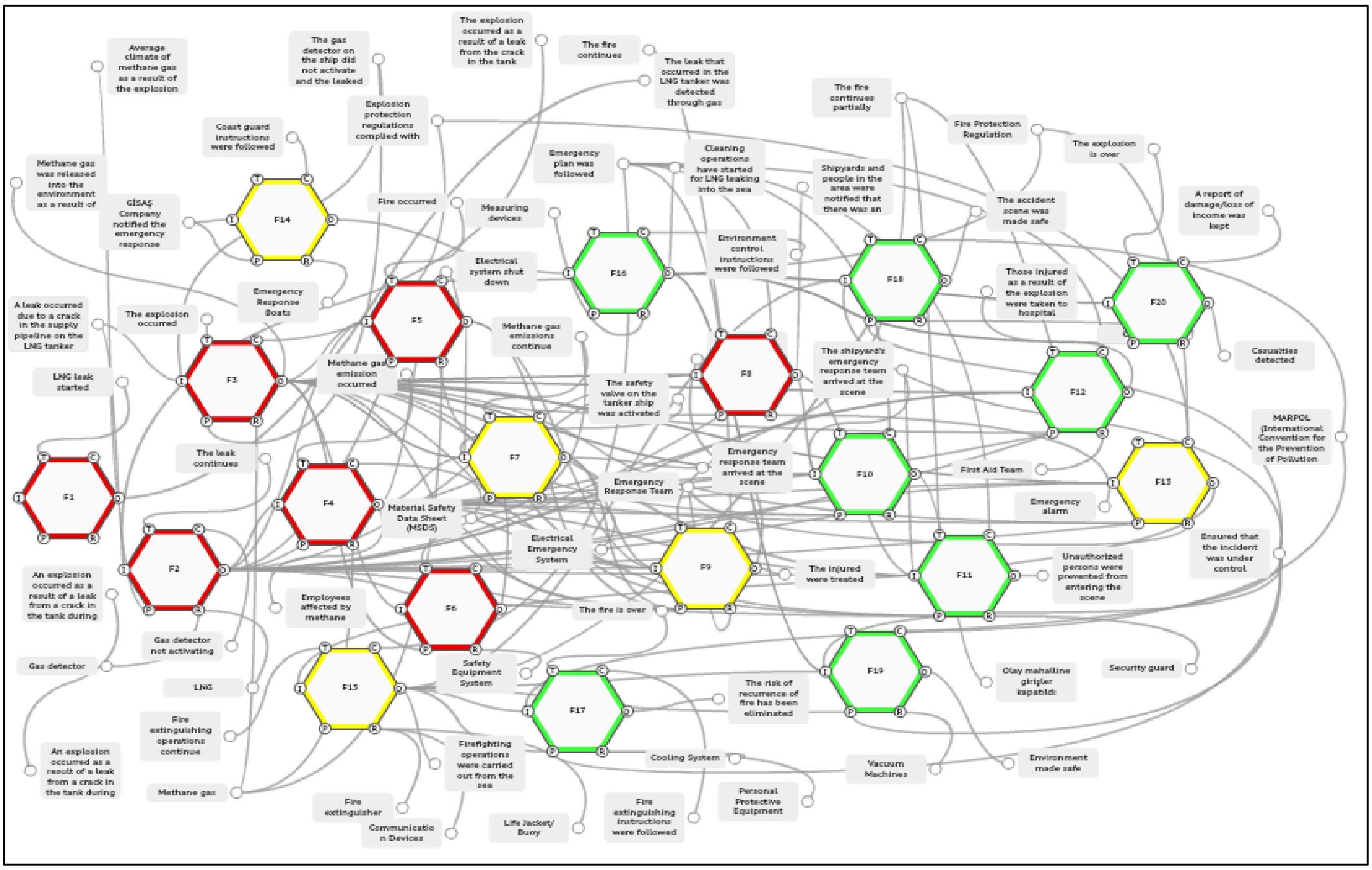

Fig. 7. FRAM analysis visualization.

all functions are interconnected, meaning that the failure of one function adversely impacts others.

The consequences of such an explosion are severe. Potential outcomes include injuries, loss of limbs, and fatalities among workers. Additionally, the hazardous chemicals in LNG can mix with the air, leading to significant air pollution. The chemical decomposition of LNG during an explosion releases a substantial amount of carbon dioxide, contributing to increased greenhouse gas levels and exacerbating climate change. Moreover, the explosion generates thermal radiation, posing a risk to individuals in the vicinity of the accident.

Environmental impacts are also significant. If LNG spills into the sea, it will result in marine pollution, endangering aquatic ecosystems. Economically, explosions in LNG operations can lead to substantial financial losses due to the high cost of LNG tanks and ship manufacturing in shipyards. Such incidents may disrupt operations, halting work until the hazardous situation is resolved, and further impacting the economy on a national scale.

An examination of extant literature reveals that...In a study by Dan et al. (2014), a quantitative risk analysis of the liquefaction system of an LNG-FPSO in an offshore environment was performed. Fire and explosion events in the upper part of the floating platform were modeled using PHAST software, and the most critical scenarios were evaluated in detail. The study also emphasized that system design in accordance with SIL (Safety Integrity Level) levels offers an effective strategy for risk management. In the present study, a qualitative analysis method, namely FRAM, was employed to examine and model fire and explosion incidents at LNG terminals. FRAM diverges from conventional failure analysis methodologies by adopting a more holistic approach, encompassing the natural functioning and failures of the system in question.

In a study by Nubli et al. (2022), CFD (Computational Fluid Dynamics) technology was used to assess the impact of LNG (Liquefied Natural Gas) on accidents. Deterministic and probabilistic methods were applied in LNG gas release and VCE (Vapor Cloud Explosions) analyses; critical zones were defined according to flammability limits. The VCE analysis guided equipment placement by examining the factors affecting the explosion pressure. CFD and FRAM methods can be complementary; one analyzes physical processes and numerical details in depth, while the other evaluates system operation and failures in a broader context.

In the study by Li and Huang (2012), the fire and explosion hazard index (F&EI) method developed by DOW was employed for the analysis of fire and explosion risks in LNG (Liquefied Natural Gas) operations. The study emphasized that the risk level, initially assessed as “very high”, could be reduced to “slight” following the implementation of safety measures and substantial reductions in the hazard radius and impact area. Furthermore, simulations utilizing VCE (Vapor Cloud Explosion) and BLEVE (Boiling Liquid Expanding Vapor Explosion) models quantitated the deleterious impacts of explosions on surrounding structures, equipment and human health, thereby demonstrating the efficacy of safety measures in mitigating risks during such events.

The analysis of fire and explosion risks in LNG operations can be approached in a holistic manner through the utilization of both quantitative and qualitative methodologies. The former encompasses the application of mathematical and statistical techniques to assess risk, while the latter involves the use of qualitative methods, such as the FRAM (Functional Resonance Analysis Model). Quantitative methods calculate the impact and magnitude of specific risks by providing numerical data through detailed modeling of physical processes. For instance, CFD (Computational Fluid Dynamics) can be utilized to mathematically simulate the propagation of gas leaks, the effects of blast radiation, and the size of damaged areas. Conversely, VCE (Vapor Cloud Explosion) and BLEVE (Boiling Liquid Expanding Vapor Explosion) models quantitatively analyze the potential consequences of fire and explosion events, providing concrete measures to reduce risks.

Conversely, the FRAM method offers a more comprehensive approach by qualitatively examining the variability of functions within the system and the interactions between these functions. The FRAM approach seeks to elucidate the interconnections between critical functions and the systemic ramifications of their failure. In the context of LNG operations, FRAM employs a more holistic approach to events such as a gas detector failure or a crack in a pipeline. This approach encompasses human factors, environmental conditions, and dynamics in system design, rather than focusing solely on physical processes.

Quantitative methods are employed to shape risk mitigation strategies by measuring the impact of specific processes; however, the FRAM method allows for the understanding of the complex interactions in the system and the wider-scale consequences of potential failures. The integration of these two approaches, when employed in tandem, facilitates a dual-faceted analysis in the risk assessment of LNG operations, thereby enabling a more comprehensive risk management strategy. The integration of these approaches has the potential to enhance the efficacy of security measures and to provide more detailed insights into the overall functioning of the system.

5. Conclusion

Today, LNG is a critical energy resource, and measures are being implemented to ensure its transportation and storage are as safe as those of other liquid fuels. However, the storage of cryogenic liquids remains a complex issue that is not yet fully understood. Historical incidents provide valuable insights into the risks associated with LNG. Notably, a major incident occurred in Cleveland, Ohio, in 1944, which significantly hindered the development of the U.S. LNG industry for nearly two decades. Another incident in 1979 involved the failure of an electrical seal in an LNG pump, which allowed gas to accumulate in a closed building, leading to an explosion triggered by an unidentified ignition source.

Although LNG does not exhibit flammable or explosive properties in its liquefied state, its rapid phase transition characteristic presents significant risks. At ambient temperatures, LNG quickly vaporizes, and the accumulation of the resulting gas in confined spaces can form flammable gas clouds. Methane, which constitutes a significant portion of LNG, is flammable within a concentration range of 5-15%. When this gas cloud meets an ignition source, it can lead to combustion and explosions due to the pressure generated (Foss et al., 2003).

Given the potential risks, particularly in industrial areas, it is crucial to implement and rigorously enforce safety measures to protect worker health, ensure operational safety, and prevent economic disruptions stemming from LNG-related incidents.

Measures that can be taken in terms of occupational health and safety are as follows;

LNG facilities must be equipped with comprehensive safety systems to mitigate risks associated with potential gas leaks and fires. These measures include the installation of advanced warning systems, such as gas detectors, fire detectors, and integrated security systems designed to detect and manage gas leaks effectively. Additionally, an automated emergency circuit disconnection system should be implemented to eliminate ignition sources arising from electrical systems during potential gas leaks.

Given that gas leaks frequently occur in gas transfer lines, the use of appropriate, high-quality materials and equipment in these systems is critical. Furthermore, periodic inspections of gas transfer lines by qualified specialists should be mandated to ensure their reliability and safety.

Alarm systems should be installed to promptly detect fires, and appropriate fire suppression systems must be designed to enable rapid intervention during emergencies. In addition, storage tanks should be equipped with safe discharge systems capable of automatically activating under high-pressure conditions. All safety measures should align with national and international standards to ensure a systematic and effective risk management approach.

A comprehensive risk assessment must be conducted in the work environment using an appropriate risk analysis methodology. This assessment should identify potential hazards and risks, and necessary precautions should be implemented accordingly.

Material safety data sheets should be prepared for all chemical substances used within the facility, and employees must be thoroughly informed about these materials. Detailed training on occupational health and safety concerning LNG should also be provided to all personnel.

Emergency preparedness is another critical component of safety management. Dedicated emergency response teams must be formed, comprising appropriately trained personnel. These teams should receive specialized training for responding to explosions and fires, and regular emergency drills should be conducted to ensure readiness and efficiency in managing potential incidents.

This study aims to elucidate the hazard dimensions of industrial accidents that could arise from system malfunctions in port areas where LNG facilities operate, using the FRAM. A scenario-based approach identified 20 functions relevant to processes occurring before and after such accidents. Among these, 7 functions were classified as high risk, 5 as medium risk, and 8 as low risk. Based on the findings, recommendations were made for implementing effective occupational health and safety measures to mitigate risks and enhance safety standards.

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