Analyzing Human Factors and Complexities of Mining and O&G Process Accidents Using FRAM: Copiapó (Chile) and FPSO CSM (Brazil) Cases

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Abstract

The study presented in this research is a systematic human factors approach comparing two striking process accidents in Latin America: the Copiapó mining accident (2010), at the San José copper–gold mine, in Chile, and the FPSO CSM accident (2015), at Camarupim offshore oil field, in Brazil. Despite being different industrial segments - mining and O&G - more similarities than differences were observed in the treatment of process safety anomalies, especially those related to major accidents. The intense interactions between workers, equipment and processes, in both industries, have been making significant developments in the edge of innovation and technology, however increasing the complexity of risks in the workplaces. Furthermore, the differences between the preparation and handling of emergency situations shows how complex, and critical, process safety is in these industrial areas. Aiming to adequately evidence how this complexity is intrinsically part of the various system that form the entire process, the FRAM (Functional Resonance Analysis Method) was utilized to model and analyses both accidents, under a human factors approach. Interactions and interrelations between LOPC, non-technical skills, resilience and technical procedures were noticed as crucial for process safety and productivity of daily operations, as well as the preparedness for emergency situations.

1 Introduction

The technological transformation of the workplaces is one of the most remarkable evolution developed by Society. Since the 1st industrial revolution, a process of changing from handicraft work to one dominated by industry and machine manufacturing, the technological changes introduced novelties of working and living, as well as fundamentally transformed humankind. As a natural outcoming, the economies have become more industrialized over the years, depending on energies such as coal and oil to build cities, enable transportation and develop different ideas, business and industrial plants. Within this context, the mining industry, with coal and firedamp, and the O&G industry, with gasoil and natural gas, worked as the fuel – metaphoric and literally speaking – for all other industries, being also party of this evolution in a feedback loop. Comparing these two different industrial areas, in a range of more than one hundred years of technical evolution, the O&G industry has developed a capability of drilling, production and processing in places ranging from coastal shallows, swamps, deep water and ice, in all over the continents. In another hand, and not so differently, the mining industry has implemented mining sites in almost all the lands of the planet, and even considering out of it [1], having considerable diverse and extreme work environments, such as glacial tundra, tropical forests and inhospitable deserts. The technology applied in mining equipment and process includes UAV-assisted (Unmanned Aerial Vehicles) to assess and obtain data in remote and dangerous sites, using photogrammetry and heavy process of information and images rendering [2]. Therefore, the workers of both industries have been exposed to extreme weather conditions, working in places where the rigors of the environment, the work itself and organizational requirements build situations and contexts with a very high risk. It is clear, therefore, the need to develop dynamic protection barriers, aiming to reconcile production demands and organizational requirements with the limitations of processes, equipment and personnel. From this need, a systematic and comprehensive approach, such as the human factors approach, seems to be coherent and adequate to analyze all these workplaces complexities and intense interactions.

2 Major accidents in process plants: O&G and mining industries

A major accident can be understood as an event of losses and consequences inside and outside an industrial site, involving equipment, personal and environment, causing solely, or a combination, of worker's injuries, toxic chemical release, explosion or fire, spillage of hazardous materials or any loss of containment [3]. Analyzing this definition and perceiving the intense interaction of process, equipment, personal and environment present in the sociotechnical complex workplaces of O&G and mining industries, invariably, undesirable loss events arise, which form the accidental chain of industrial disasters. In this sense, undesirable events such as Deepwater Horizon platform (2010), Mariana tailing dam (2015), Abqaiq refinery (2019) and Brumadinho tailing dam (2019) shows that major accidents in O&G and mining industries causes losses and impacts in all sectors of Society. Specifically in the O&G industry, in 2019, the activity with the highest number of fatalities was "lifting, crane, rigging, deck operations" (29%) with four fatalities as a result of four separate incidents; three fatalities (21%) were reported in two separate incidents in the "drilling, workover, well services" activity category, and two fatalities in two separate incidents were reported in the "maintenance, inspection, testing" activity category [4]. However, the sector poses serious dangers to human health and the environment. In a similar way, in the mining industry, ground failures resulting from poorly supported stopes have led to injuries and fatalities in several mining sites all over the World. Dust and fumes from drilling and blasting of ore present health threats due to poor ventilation, causing immediate intoxication or pneumoconiosis overtime [5]. All these O&G and mining accidents enfolded process, equipment and systems that were operating under organizational rules, high technology, skilled personal and hazardous environment, needing, therefore, a systematic and comprehensive approach that considers the complex interaction of organizational, environmental, individual and technological elements.

2.1 Copiapó mining accident (Chile) in 2010

The northern deserts of Chile are the world's largest producer of copper, and most Chilean miners work in modern copper mines under the supervision of traditional multinational companies including Anglo American and BHP Billiton [6]. With more than 50 percent of the nation's export earnings coming from mining, Chile has long been a world leader in both mining technology and mining operations. Chuquicamata, the world's largest open pit mine, is run by the Chilean government copper company known as Codelco. Mining jobs are highly coveted as both lucrative and safe - considering that safety in the world of mining is relative [7]. Combining the risks of inexperienced drivers conducting truckloads of ammonium nitrate explosives, hundreds of miners setting dynamite charges inside caves every day, and all of this taking place in Chile, a nation known to have the world's biggest earthquakes [8], and accidents are almost a certainty, generating an organizational culture, in all mining companies in the area, that accidents were common, normal and inevitable part of the mining jobs in this part of the World [9]. The geology of Chile plays a crucial role in the mining process industry, once the earthquakes are almost daily in some areas of the country, being from almost noted till severe consequences. Just along the Pacific coast of South America, the Nazca Plate hits up against the coast of the continent, and them dips down, sliding under the South America Plate and, consequently, causing the geologic instability in the mines all over Chile [10]. There are many structural geological movements around the World such as faults and contact fracture zones, as some of them affect mining areas [11]. Figure 1 shows how this dynamic Earth movements happens in the continent's geography.

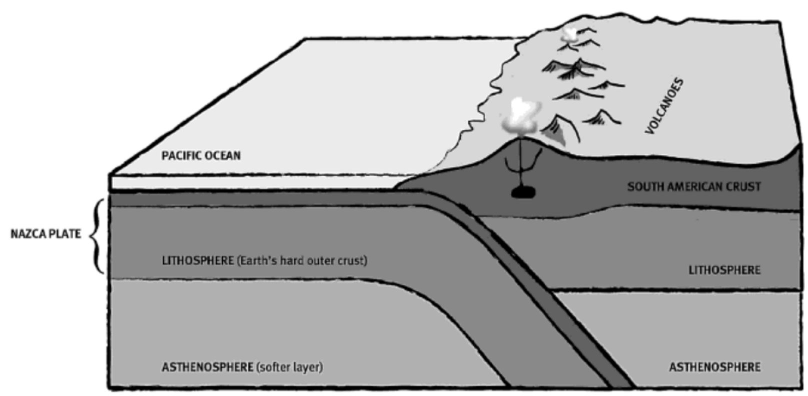

Figure 1: The Nazca Plate sliding under the South America Plate.
Source: Aronson, 2019.

In the South America Continent, located in Chile, the San José mine is a copper & gold extraction facility, placed in the Atacama Desert, 45 kilometers north of the regional capital of Copiapó, in northern of the country [10]. This mine is owned by the San Esteban Mining Company, a Chilean mining company dedicated to the production of copper and gold, founded in 1957, whose headquarters are located in Providencia, Santiago Metropolitan Region [7]. The San José mine start its operations in 1889 and till the 2010's accident, maintained its uninterrupted operation, despite safety violations, fines from the government, degradation of the work environment and a history of serious accidents, especially due to the geological characteristics of the mine [12]. The rocks inside the San José mine were so sharp that the miners knew that even brushing up against the wall was like scraping a razor across their skin [7]. The sum of this hostile environment with the organizational culture that stimulated production, instead of safety, invariably results in the occurrence of accidents. A serious reminder of this combination came on July 5, 2010, few weeks before the accident analyzed in this research: a block of rock equivalent of twenty refrigerators seriously injured a left leg of a worker, being amputated during the medical assistance soon after the accident [7]. Immersed in this culture that accidents are normal, the worker said in hospital "- I am lucky," alluding that his accident could have been much worse, even fatal.

The mining process industry is indeed a hazardous environment, having worker's extremities, hands and foot, with the highest injuries percentages. The injuries of the upper limbs are mainly caused by contact with the machinery and the roof of the mine. Lower limb injuries mainly occur as a result of stepping or kneeling on an object, stepping into the cavities or contact with the machinery, especially non-protect ones, which has its covers to improve or not stop the production [13]. The two major issues in front of the world mining industry are work safety and protection of ground environment when carrying on underground mining activities, enabling the effective control of rock pressure and ground movement, the protection of the environment and the adequate disposal of a huge amount of solid waste [11]. In the San José mine, more than a century of picks, dynamite and drills had riddled the mining site with so many holes and tunnels that new workers would wonder aloud how the roof did not fall down on the many passageways. Even the experienced employees had no way of recognizing that after 111 years of operation, after millions in gold and copper ore had been wrenched from every corner of the now labyrinthine tunnels, the mine had also been stripped of its support structure. Like a house of cards, the mine was now delicately balanced [7]. This uncontrolled used of dynamite and its misuse to clean ways through the San José mine transformed the internal paths into a complex and unstable chain, bringing geological and structural uncertainty to most tunnels, refuges and other workplaces built in the subsurface. Figure 2 present a scheme of this mine, highlighting the point of the accident.

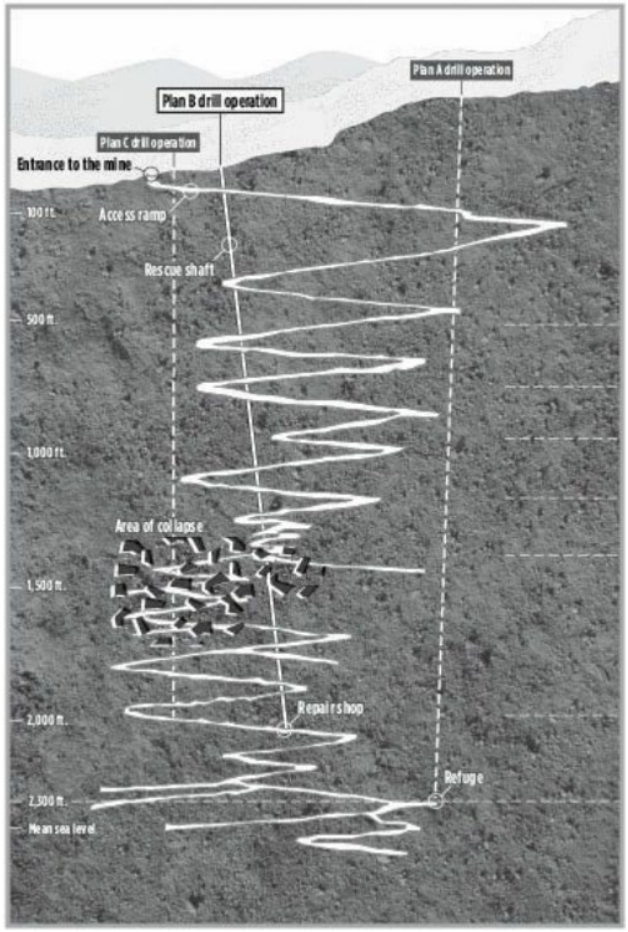

Figure 2: The San José mine and the points of accident and rescue.
Source: Franklin, 2011.

Particularly, even as a consequence of the organizational culture in this subsurface workplaces, the employees of San José mine worked not at the safe modern mines but instead belonged to the riskiest subculture of this entire industry: low-tech, rustic miners known locally as “Los Pirquineros.” [7]. Also, the work environment inside the mining were in the time of the accident far from the ideal, even far from the adequate and approved by OSHA (Occupational Safety and Health Administration). Inside the mine, the temperature rarely dipped below 35 degrees Celsius, and the workers guzzled three liters of fresh water a day, yet still lived on the fragile border of dehydration. Humidity was so thick that their cracker biscuits became a soft mass almost instantaneously, and ultimately became uneatable [12]. Later in this article, the Human Factors approach will be presented, where environmental elements, such as these presented here, play a fundamental role in the performance of workers and, consequently, in the efficiency of work activities within the mine. And as harmful as that, if the workers are not injured by the mine rigors and dangers, they slowly die from lung problems. Long-term exposure to the gases, mineral dust and grit led to silicosis, a pneumoconiosis caused by the successive accumulation of particulates in the pulmonary alveoli, permanently clogging the lungs, causing serious, and mostly fatal, respiratory issues. With all these elements, history, and consequences of injuries for workers, both in the short and long term, the accident at the San José mine seemed inevitable under the complex combination of the circumstances. Figure 3 shows the mouth of San José mine, few days after the occurrence of the accident.

Figure 3: The mouth of San José mine.
Source: Franklin, 2011.

2.2 FPSO Cidade de São Mateus accident (Brazil) in 2015

The FPSO Cidade de São Mateus (FPSO CSM) is a floating production, storage and offloading unit operated by BW Offshore Brazil, in gas fields under concession to Petrobras, the Brazilian NOC. These fields, Camarupim and Camarupim Norte, are in the Espírito Santo Basin within Brazilian waters, and since the first day of operation its main production was non-associated natural gas with no oil wells connected to the platform [14]. All processed gas was transferred through a pipeline connected to the Cacimbas Gas Treatment Unit (located onshore). Gas process operations produced a liquid fraction referred to as natural gas condensate. This condensate was occasionally exported through the gas pipeline but, more commonly whilst in production, it was stored in cargo tanks for later export by tanker [15]. In this offshore facility, in the morning of February 11th, 2015, an explosion inside the pump room onboard FPSO Cidade de São Mateus (FPSO CSM) unfortunately killed nine workers and injured 26 other ones within Brazilian Jurisdictional Waters. A condensate leak occurred in the pump room at approximately 11:30 on 11th February 2015, while the stripping pump was being used to drain liquid waste from central cargo tank number six. The leak occurred in a flange in the main piping system inside the pump room, due to failure of a spade in the flange connection. The spade had probably been fabricated on board and it failed due to a pressure overload caused when the pump was operated against a closed valve [16]. Figure 4 presents an illustration of this type of platform.

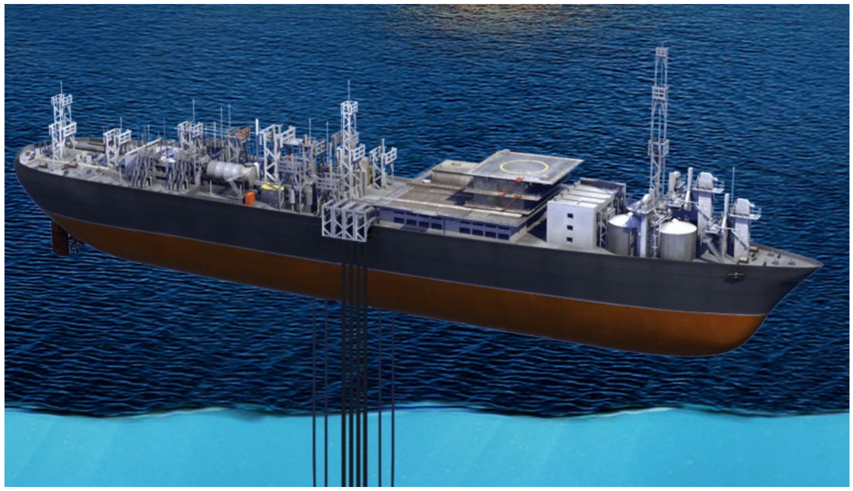

Figure 4: Illustration of a FPSO (Floating, Production, Storage and Offloading) platform.
Source: Petrobras, 2020.

Despite the well-known leakage and the confirmed presence of explosive atmosphere, the production was continued for another ten minutes until a management meeting decided to stop operations and send the first team into the pump room [18]. It is not clear from the investigation report when the stripping pump was stopped, but it is assumed that this pump also was kept running for approximately ten minutes, which severely increased the risks. The ventilation system was stopped due to the gas detection, implying that no dilution of the explosive atmosphere was attempted, which would increase risks for personnel sent to the pump room [16]. The emergency response team was set in motion and regular activities executed by them regularly was replaced by emergency response demands. Thus, safety technicians became brigade leaders, production operators became members of the brigade teams and, similarly to other functions, a response structure was formed, as designed by the process plant emergency plan [15]. According with both ANP [18] and Brazilian Navy [19] official reports of this accident, this team should initially be mobilized for emergency, as it really had been. However, after confirming the presence of an explosive atmosphere, with the portable detector alarming 100% of the *Lower Explosive Limit* (LEL) [16], the entire team should have been demobilized and the shutdown procedures for the entire process plant should have started. The presence of the first team in the pump room, to investigate the source of the gas detection, the second team, to assess the repairs required for production and the third team, to control and cleanup the leakage with absorbent blankets, hoses, ladder and tools were crucial for the fatalities [20]. All teams remained inside the pump room and on its proximities, and few moments after the control and cleaning actions starts, while still the maintenance team was screwing down the piping connections, a powerful and sudden explosion occurred at 12:38h [15], as can been seen by the images from CCTV system of the FPSO, present in figure 5.

Figure 5: FPSO CSM explosion caught by its CCTV system.
Source: C. Morais et al., 2017.

Both personnel from Petrobras and BW, involved in the operation, management and emergency response of FPSO CSM, were convened by the Brazilian regulatory body for the O&G area (ANP - Agência Nacional do Petróleo, Gás Natural e Biocombustíveis), aiming to contribute to the clarification of the facts and practices onboard of the platform, before the accident [15]. The accident investigation process identified twenty-eight root causes of this accident using the Fault Tree Analysis technique, generating an official report. Besides this, sixty recommendations directed to oil production and offshore natural gas processing was issued by the investigation team, looking for the avoidance of similar accidents, being their implementation mandatory for the companies involved in this accident [18].

3 Materials and methods

This research was developed following four particular steps, considering the accidents report, the applied methodology, worker's validation and discussions. The information related to accidents were collected from their official reports, being ratified by books and articles that addressed these events. These four steps were designed to widen accident's analysis, using a methodology capable of modelling the complex interactions of sociotechnical system such as modern O&G and mining workplaces. In this sense, FRAM (Functional Resonance Analysis Method) was the choice, as it combines this capability, in addition to being considerably applied for the analysis of complex work environments, whether in normal operation or not [21].

3.1 The FRAM methodology

The FRAM is a methodology that analyses and describe the nature of workaday activities in complex sociotechnical system, both in past and future events, allowing, thus, an accident investigation, as well as risk assessment studies [22]. To build a FRAM model, the first step is the identification and description each of the functions, which can be human, technological or organizational, depending on its natures in the system. It aims to detail how a task is done in a real everyday activity, rather than to describe it as an overall task or procedure [23]. The graphic representation of a function is a hexagon, where each vertex of this hexagon is the determination of one of the six aspects of the FRAM methodology function: Time, Control, Output, Resource, Precondition and Input [24]. The capital letters, begging each aspect observed, marks its difference from an ordinary input or output of a simple flow chart; they are the aspects that form the FRAM model and determined by its methodology as the connections between functions. These aspects, and their interconnections between functions, are precisely what allow an adequate representation of the complexity of activities (and accidents) of the O&G and mining process plants. A representation of a FRAM function, using the software FMV® [25] is presented in figure 6.

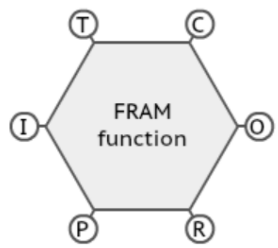

Figure 6: Representation of a FRAM function using FMV®.
Source: Authors, 2021.

The FRAM is a methodology that enables a wider and systematic comprehensive analysis, describing the intrinsic nature and real interactions of work activities, notably in workplaces where there is an intense interaction between technology, process and workers, such as O&G and mining industries, but not limited to these. This makes the analysis provided by the FRAM a systematic understanding of how things work – whether it is regarding accidents resulting from improvisation in workplaces, construction site analysis, aircraft maintenance activities or shoe manufacturing [26]. The development of this analysis based on the human factors approach enables the identification of organizational, individual and technological elements related to the accident, expanding the understanding of this event. Furthermore, in this research, FRAM is being used in an unorthodox way, since important factors, such as communication and culture, are modeled as functions, along with typical functions.

3.2 The human factors approach

The evolution of work environments, in all its dimensions, must have as a fundamental premise the integration of productivity and safety, in order to guarantee the sustainability of the business. From the first studies of industrial safety in the 30's, much has evolved in terms of technology, transforming the workplaces of the first Industrial Revolutions into true complex sociotechnical systems [27]. Thus, consider that workplaces of industries with considerably technological development – aviation, O&G and mining – are formed by linear and simple system is not only a misconception, but also inadequate to understand its functioning, both in normal operation as in emergencies. To understand what happens in these places, it is necessary to use methodologies, tools and concepts that have also evolved, at the same level of the system under analysis, such as the human factors approach. In this sense, human factors are understood as the scientific study, in the work environment, of the interaction between organizational, individual and other factors [28]. For the US Federal Aviation Administration, human factors are a multidisciplinary effort to generate and compile information about human capabilities and limitations and apply that information to equipment, systems, software, facilities, procedures, jobs, environments, training, staffing, and personnel management to produce safe, comfortable, and effective human performance [29]. Focused in O&G domain, for the International Association of O&G Producers, human factors addresses the interaction of people with other people, with facilities and with management systems in the workplace [30]. Based on these studies and aligned with the evolution of the process industries workplaces, human factors are all those factors that influence human performance in their work activities; these factors act together and can be technological, environmental, organizational and individual, among others. This approach will be applied in this research and figure 7 presents its graphic's representation.

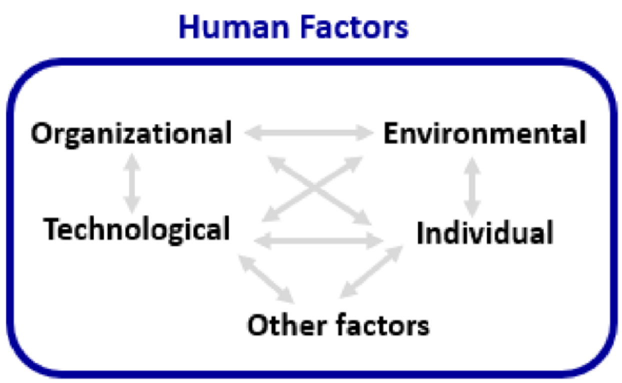

Figure 7: Graphic representation of the human factors approach.
Source: França et al., 2020.

Inserted in this context, during the events leading up to accidents, people are acting in a way that makes sense to them at the time. All their knowledge, training, experience and inputs from the environment combine to influence the decisions made and the actions taken. The human factors approach allows a comprehensive and systemic analysis of all the factors that may affected human performance, having this approach from the human element, and not only focusing on it. Notice that this analysis considers four major segments, not only limited to the individual, which could lead to a simply and mistaken analysis of human errors. Indeed, a human failure, which is included here in the individual dimension, will always be present, however, on a considerably smaller scale. This is even more noticeable when the human factors analysis identifies the technological, environments and organizational elements that contributed to the chain of events of the accident. Aiming to develop this analysis, the FRAM was employed in this research to analyze two different major accidents of O&G and mining industries, the FPSO Cidade de São Mateus accident (Brazil) in 2015, and the Copiapó mining accident (Chile) in 2010.

4 Results and discussions

Unlike traditional risk analysis or accident analysis methodologies, such as HazOp and FMEA, FRAM enables a systematic and comprehensive analysis of a sociotechnical system, without the linearization of complex interactions [32], both for normal operating situations (normal operation) and for out-of-control situations (accidents and emergencies). The adoption of this methodology, in these two accidents, aims to expand the understanding of these events, especially regarding the complex interactions and organizational elements.

4.1 Analyzing the FPSO Cidade de São Mateus accident (Brazil) with FRAM

Based on the documents of the FPSO Cidade de São Mateus accident, a FRAM model of this event was developed under a human factors approach. This analysis enabled a wider comprehension of this event, understanding how the organizational elements are deeply rooted. This model is presented in figure 8.

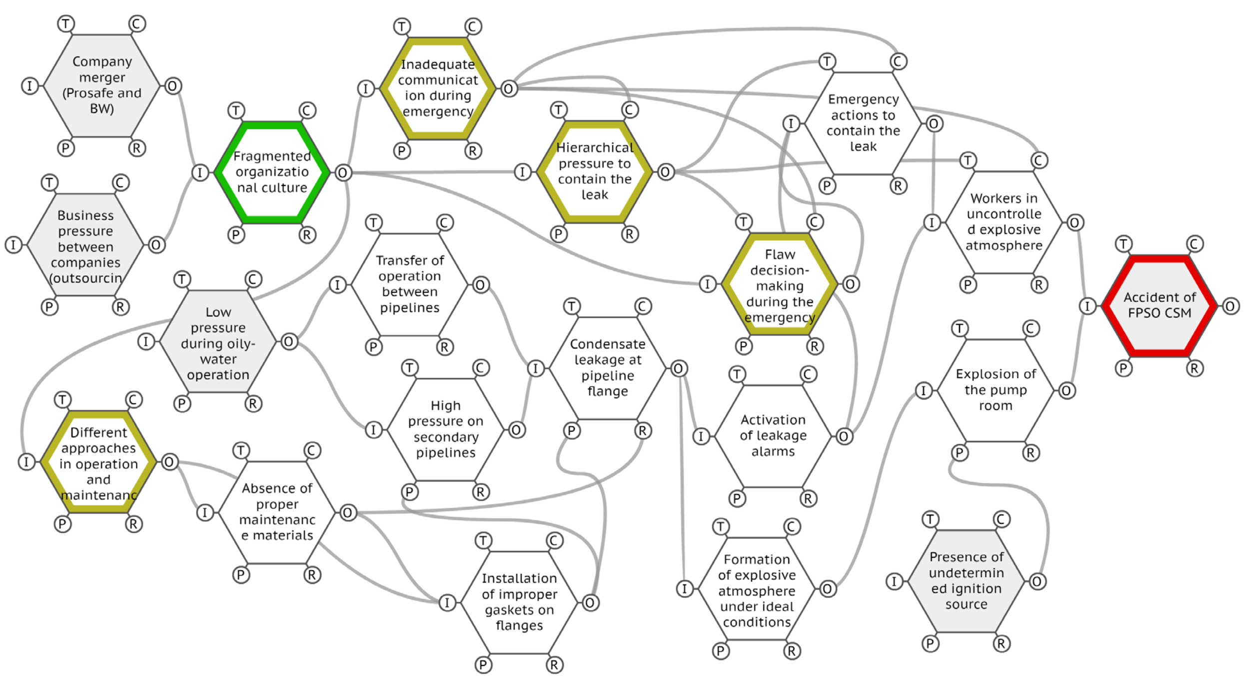

Figure 8: FRAM model of the FPSO CSM accident (2015).
Source: Authors, 2021.

The function “Fragmented organizational culture”, highlighted in green, is a critical one, once resonates this fragmentation over four different functions: “Inadequate communication during emergency”, “Hierarchical pressure to contain the leak”, “Flaw decision-making during the emergency” e “Different approaches in operation and maintenance”. These four functions, in turn, play a crucial role in the causes of the accident, being highlighted in yellow. The validation of this model was carried out by three online meetings with FPSO CSM workers who were working on this platform at the time of the accident, but not during the accident. From the first model built, to the final model presented here, some changes were made at the request of the workers, including two specific functions.

4.2 Analyzing the Copiapó mining accident (Chile) with FRAM

Also based on the documents of the Copiapó mine accident, a FRAM model of this event was developed under a human factors approach. This analysis enabled a wider comprehension of this event, understanding how the organizational elements are deeply rooted, quite similar to the analysis developed performed for the FPSO Cidade de São Mateus accident. This model is presented in Figure 9.

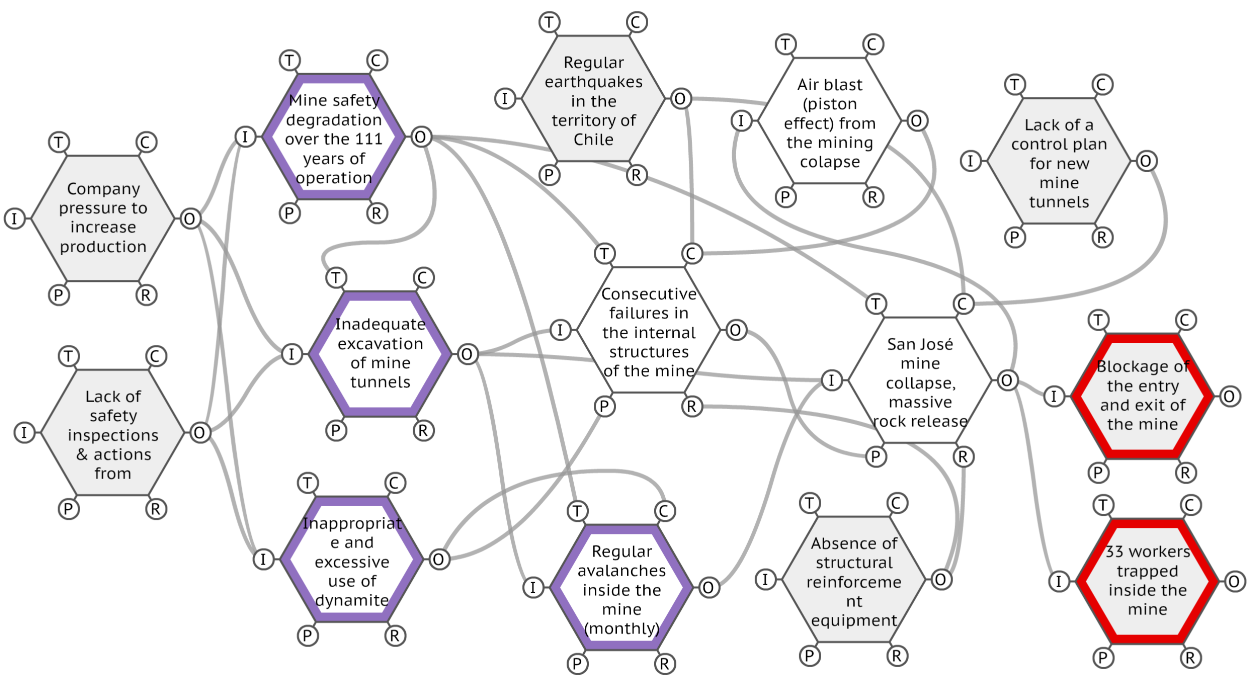

Figure 9: FRAM model of the Copiapó accident (2010).
Source: Authors, 2021.

The function “Mine safety degradation over the 111 years of operation”, highlighted in purple, is a critical one, once resonates this fragmentation over four different functions: “Inadequate excavation of mine tunnels”, “Regular avalanches inside the mine (monthly)”, “Consecutive failures in the internal structures of the mine” e “San José mine collapse, massive rock release”. In particular, two of these functions were critical to the accident, being highlighted in also in purple, namely “Inadequate excavation of mine tunnels” and “Regular avalanches inside the mine (monthly)”. The validation of this model was carried out by two in-person meetings in Santiago, Chile, and one last online. In the in-person meetings, one of the 33 survivors participated in the discussion. From the first model built, to the final model presented here, several changes were made at the request of the workers, adding and changing various functions.

4.3 Human factors analysis of the Copiapó and FPSO CSM accidents

Despite being two different FRAM models, with different functions, connections and resonances, there are many similarities between these accidents modelling, especially in the organizational dimension of human factors. The effect of organizational culture on daily decision-making and, consequently, on the chain of events of an accident, cannot be evidenced by a HazOp or FMEA, but it is clearly perceived in the two developed FRAM. The function “Fragmented organizational culture”, highlighted in green in the FPSO CSM FRAM, is directly and simultaneously connected with “Inadequate communication during emergency” and “Flaw decision-making during the emergency”, which are two causes of the accident, being identified as this in the official report and validated by the workers. Another critical organizational element affected by the resonation of this fragmented culture is the function “Different approaches in operation and maintenance”, where organizational decision regarding the way to operated and maintain the process plant altered its reliability, generating the absence of proper maintenance materials and the installation of improper gaskets on flanges (functions “Absence of proper maintenance materials” and “Installation of improper gaskets on flanges”). This last one – improper gaskets on flanges – was the technical cause of the massive hydrocarbon leakage (function “Condensate leakage at pipeline flange”), the most prominent cause of this accident [16]. This organizational dimension, in sociotechnical complex workplaces, it is a key issue to be analyzed, as an in-depth analysis of the Challenger’s space launch pointed out, once it unveiled interactions through organization culture, hierarchical layers and, ultimately, decision-making chain, from the factory floor to the top management [33].

Specifically, in the mining industry, considering the recent accidents of Mariana (2015) and Brumadinho (2019), both in Brazil, emphasizes the need of understand the organizational dimensions and their multiple interactions shows that every accident involves complex social processes, full of disputes, political resistances, and/or spaces for freedom, dialogue, and cooperation [6]. The effect of organizational culture on Copiapó mine accident was perceived over more than 100 years of safety degradation, represented by the function “Mine safety degradation over the 111 years of operation”, which fed, and fed back, a series of systemic organizational failures, ranging from the daily maintenance of the mine, represented by the “Consecutive failures in the internal structures of the mine” function, to the development of an organizational tolerance for avalanches, with their occurrence being reported as “normal” at least once a month, as evidenced in the “Regular avalanches inside the mine (monthly)” function. In fact, the way a company develops its procedures and conducts its daily activities can feed a culture of increasing tolerance of safety degradation, feeding the chain of events that leads to an accident [9]. Also critical, the function “Inadequate excavation of mine tunnels” resonated simultaneously for the regular avalanches and the instability of internal structures, enhancing its effects all over the mine tunnels. Particularly in the Copiapó mine, the function “Inappropriate and excessive use of dynamite", another critical function highlighted in purple, has a direct connection in "Consecutive failures in the internal structures of the mine", and increased the damages in internal structures, accelerating the failure process that collapsed the mine, as reported by the miners. This function was not contemplated in the preliminary model, but in the in-person conversations, it was evidenced in all discussions, being then classified as critical.

The organizational functions "Mine safety degradation over the 111 years of operation" and "Fragmented organizational culture", despite coming from different accidents and industries, both have the same resonating effect over the complex chain of events that led to the accidents at the Copiapó mine and FPSO CSM. Indeed, analyzes developed with methodologies appropriate to the complexity of their systems, such as the FRAM done for these two accidents, in which the core functioning of the complex sociotechnical system is canvass, enables the recognition of the organizational culture role in the chain of events of an accident. This recognition favors the understanding of how a company's culture is manifested in all hierarchical structures and, consequently, the understanding of how it contributes to an accident. For a long time, it was only attributed to the unsafe acts of people, or machine failures, the causes of major accidents [34], being myopic for how organizational culture can affect an entire work system. In this aspect, reliability dealt with the guarantee of equipment functionality, while merely behavioral theories or reliability itself, but only focused in human errors, dealt with unsafe acts [35]. It is possible to notice, after a human factors analysis of these two accidents with the FRAM, that the effect induced by organizational factors over the company is ample, extensive and permeates all hierarchical structures, dynamically influencing a complex network of sociotechnical interactions.

Additionally, both industries – O&G and mining – have centuries of tradition and it is an inseparable part of the evolution and history of Humanity. Thus, the change in culture, promoted by the natural evolution of the sociotechnical systems of the work environments, despite being accelerated by technology [33], involves a slow and gradual evolution of safety. The evolution of safety, however, is a key issue not only for regulation, standards and accidents avoidance, but it's an intrinsic need to keep the business going. Only companies that integrates all their structures and sectors evolve can be competitive and perennial in the globalized business chain in the 21st century [36]. Like mining industries, the O&G industry is also part of the capitalist system, where terms such as profit, labor, surplus value, subsistence and exploitation are clearly present. Particularly in the technological O&G, all these appear in a glaring way, since the investments, costs and services involving this area runs over billions of dollars [20]. In this sense, examining the FRAM from the Copiapó mine accident, it was possible to comprehend how the top management pressure for production and the lack of safety inspections have both contributed for this event, nurturing a normal accidents culture over 111 years of safety degradation. In the same way, examining the FRAM from the FPSO CSM accident, it was feasible to understand how the merger between different companies driven only by financial motivation was a key factor to have a fragmented organizational culture. Hence, this fragmented organizational culture influenced the communication, decision-making and actions during the emergency activities.

5 Conclusions

The concepts and findings of this study enabled a wider understand that the work itself is not something static. It faces variations of different natures, whether from the environment itself, the technology in the workplaces, the organizational interrelations and layers, as well as the workers characteristics and how them interacts with all this sociotechnical system. These variations occur several times a day, both in routine actives and emergency situations, allowing a non-stopping adaptation between the work as prescribe and the work as done. Thus, the different production goals to be achieved, plus the organizational culture and the workers skills (technical and non-technical) promotes a dynamic variability of the entire system, allowing an also dynamic response for the complex combinations that may arise from all of this.

In this context, industries that have equipment, process and system of high technology, such as O&G and mining industries, has a high level of complexity on its daily operations, demanding a constant adaptation between system demands and work conditions. Thus, looking for an equilibrated and adequate analysis of such workplaces, both for normal operations and accidents, it is needed a wider and systematic comprehension of the complex interactions that arise from these workplaces, simultaneously considering the organizational, technological, environmental and individual elements that shapes these sociotechnical systems. The FRAM modelling of both accidents showed that the organizational culture is a factor which is deeply rooted in all of the company's hierarchical structures and is therefore one of the contributing elements of both accidents. Also, the rigors of the workplaces, offshore in the O&G area, and underground in the mining area, generate complex interactions in all labor relationships, affecting the performance of workers, service providers and leaders.

The complex interdependence between the functions of the FRAM models presented in this study demonstrates that the analyzes of these accidents are not something simple or linear, but something intricate and semipredictable, which depends simultaneously on subjective elements, such as the organizational culture, and objective elements, such as the use of dynamite in sub-surface and the use of improper of materials for maintenance. With this, traditional risk assessment tools and methodologies can't adequately find these complex sociotechnical relations, which compromises the effective analysis of the accident, or, at worst, bring a misinterpretation. In this sense, when seeking to promote process safety in workplaces of high complexity and technology, such as those presented in this research, an analysis of human factors, in addition of identifying the linear elements present, also identifies the interactions and complex elements, comprehending technological, individual, environmental and organizational dimensions. As can be seen in the analyses developed here, the organizational elements weigh on a crucial role for both productive and safety performance in mining and O&G industries.

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