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Identifying Emerging Risks Using the Functional Resonance Analysis Method (Fram): A Case Study of an Air Separation Unit in a Steel Company

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Abstract

Background: Socio-technical systems are inherently complex, non-linear, uncertain, and dynamic. The complexity of the relationships between the components of these systems is unfathomable, and it is very difficult to predict, model, and analyze their components. In such systems, safety is not a linear and direct process. Thus, the purpose of this study was to identify emerging risks using the Functional Resonance Analysis Method (FRAM), which can provide a new perspective in completing traditional risk analysis methods.
Materials and Methods: The study analyzed the air separation unit process in a steel industry for performance resonance by collecting data through field studies and expert opinions. Using the FRAM method, risks associated with the unit process were evaluated and analyzed.
Results: Ten essential functions of the system were identified. The results revealed that the two functions of "air compression" and "distribution and storage" had high variability, and a high resonance was observed in these two functions. The other functions also indicated moderate and low variability.
Conclusions: The study identified ten essential functions in an air separation unit, with “air compression,” “distribution,” and “storage” showing high variability and resonance. Improving their consistency and reliability could benefit the system. Other functions had moderate to low variability. Future work should focus on optimizing all functions, especially those with high variability, to address tight interactions and resonance issues. The analysis offers a functional map for targeted system improvements.

Keywords: Risk Assessment, Safety Management, Steel

Introduction

Complex socio-technical systems include some subsystems and sub-activities that are interrelated in known or unknown ways [1]. These systems generally consist of elements or functions including man, technologies, and organizations [2]. Examples of socio-technical systems include healthcare, aviation, manufacturing, electrical industry, and automotive [3]. These systems are inherently complex, nonlinear, uncertain, and dynamic [4]. The complex nature of the interrelationships between the constituents of these intricate systems is characterized by an exceedingly complex structure. This type of system poses major difficulties in terms of the prediction, modeling, analysis, and engineering of its components, as well as for the decomposition of the system into its constituent elements [5]. The complex interrelationships between humans and their environments, including technologies and organizations, indicate that safety in such systems is not a linear process [4]. Emerging risks in safety refer to new and upgraded technologies that create potential hazards for workers. These risks are often generated by changes in industries and can pose challenges for safety management [2].

There are two different methods for managing safety in organizations: Safety I and Safety II. In the Safety I perspective, the focus is on reducing adverse outcomes, such as accidents, incidents, and near misses [4]. Fig. 1 displays the concept of safety philosophy I.

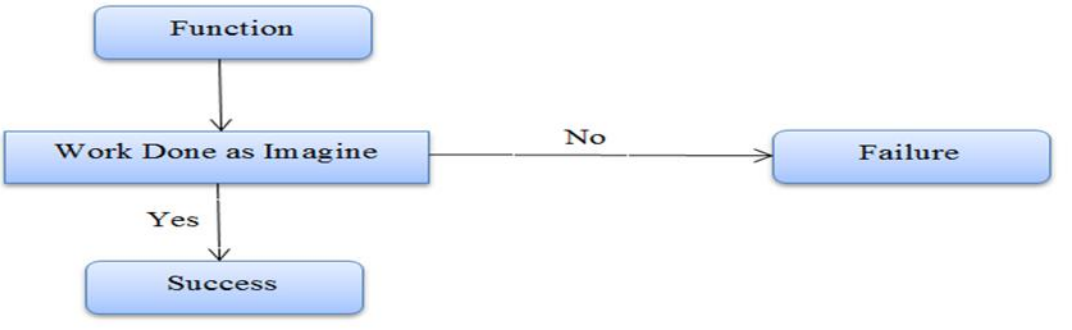

Fig.1. Safety I Philosophy

The main idea behind the established techniques for risk and incidents analysis in the Safety I approach is based on event chains. Unexpected outcomes and potential incidents cannot be predicted by considering event chains or possible component failures in complex socio-technical systems [6]. Safety I-related tools do not consider possible connections and interdependencies among the three elements of technology, human, and organization for incident modeling and risk analysis [7]. Interactions between elements are of great importance as these interactions may be nonlinear and dynamic [8].The non-linear nature of the dependencies may lead to aggravation of the adverse consequences of complex systems [9]. In addition, there is a shift from "human error" to "human performance variability" in the analysis of risks and accidents in complex systems [10]. Conventional tools in the Safety I approach are incapable of understanding the risks associated with performance variability [11]. Therefore, to deal with safety and risk issues in complex socio-technical systems, there is an obvious need to modify conventional approaches [12].

Over the last two decades, a new approach has been presented with an emphasis on studying successes instead of failures to create a better understanding of system safety. To explain the differences between this approach and the classical safety approach, Hollnagel proposed that this new approach be called safety II (against safety I for the classical safety approach). Thus, Safety II is the name used to explain the new approach in safety and distinguish it from the classical approach. Safety II recognizes that the entire system cannot be understood without fully understanding its internal components. Safety II focuses only on adverse events in everyday work and situations where everything is right [13].

The steel industry has experienced growth to support infrastructure and development. The processes involved in producing steel are complex and come with hazards. Despite the presence of safety regulations and guidelines, working conditions in the steel industry remain unsafe, leading employees to engage in unsafe practices. Over time, there has been an increase in accidents, with both accident rates and fatalities on the rise. Note that there is currently no guidelines or comprehensive plans in place to implement and improve safety protocols. These accidents occur because employers fail to comply with the provisions. In addition, it is unfortunate that contract laborers working in the steel industry often become victims of accidents [14].

The Functional Resonance Analysis Method (FRAM) model was introduced by Hollnagel in 2004 as a systematic incident investigation method [15]. FRAM is a performance-based systems approach to examine safety-related problems and challenges in socio-technical complex systems [10]. Unlike most conventional risk assessment approaches that focus on the root causes of failures, FRAM focuses on understanding how activities can be coupled and how variations in day-to-day operations and activities may lead to undesirable and unexpected outcomes [15, 16].Considering the viewpoint of FRAM, unacceptable outcomes such as accidents occur as resonances and are not usually attributed solely to human or equipment failures. This means that the connections between components, inputs, and outputs, as well as causes and consequences, lead to the emergence of favorable/expected and unfavorable/unexpected consequences [10]. FRAM describes how complex socio-technical systems work and emphasizes functional aspects, dynamic interactions, and functional diversity rather than physical aspects [17]. These analyses have enabled the identification of potential risk patterns before incidents. Organizations can then monitor the system to detect early signs of resonance and intervene with barriers or changes to dampen variability before it compounds into safety threats. Overall, FRAM provides a method to anticipate and manage the complex dynamics that underlie both routine operations and rare catastrophes in high-risk work environments. The functional perspective it introduces has been valuable for revealing new safety insights inaccessible to other accident models focused on component failures [18].

Hulme et al. concluded in a study that FRAM can find suitable solutions to maintain work operations within an acceptable margin of safety [15]. In Grant et al.'s study, it was found that FRAM's ability to detect changeable resources is critical to safety management, as functions can be coupled and lead to unexpected results [7]. In another study, Lee et al. concluded that FRAM may help model complex interactions and performance variability that can lead to the identification of potential risks. It was also found that FRAM-based frameworks can be developed to identify operational risks and contribute to risk management by recognizing dynamic functions and activities among them [19].

In most industries, including the steel industry, with a traditional approach to safety, issues of organizational safety and accident analysis are observed based on the linearity and certainty of the accident causes in a chain that are caused by operator error. This is despite the fact that unlike the traditional approaches that consider systems as stable and controllable, in new approaches, due to the strong interactions between components and the complexity of the process, the occurrence of events in these systems is considered untraceable. Thus, the traditional risk analysis methods are not suitable for assessing the risks in socio-technical complex systems, and as such methods should be found that are appropriate to the characteristics of these systems in order to prevent catastrophic events. The aim of this study is to identify emerging risks using the functional resonance analysis method (FRAM), which can provide a new perspective in completing traditional risk analysis methods in the steel industry.

Materials and Methods

The data collection method in this study was based on the semi-structured interview method and direct observation. Studying the instructions and process workflow as well as forming a specialized panel of engineers and operators of the air separation unit were other methods of data collection. These data constituted the basis for constructing the FRAM method.

Table 1. Specialized team members

No.	Specialist	Number of experts	Work experience (years)
1	Head of the oxygen and hydrogen production unit	1	17
2	Process expert	3	3-14
3	Automation and instrumentation expert	2	7
4	Production shift foreman	1	21
5	Safety consultant expert	1	4
6	Site operator	3	5-7
7	Control room operator	1	9

Air Separator Unit: Air separation by cryogenic or cooling methods is used to produce pure oxygen and nitrogen in gaseous form or by internal compression in the form of liquid oxygen, nitrogen, and argon. The cryogenic air separation process, initially developed by Carl von Linde and later improved by George Cloud is used for industrial-scale production of oxygen, nitrogen, and argon. The steps involved in this process include plant preparation, air compression, cooling, purification, distillation, and storage as well as distribution of liquid and gas products. Fig. 2 reveals the flow diagram of the air separation unit.

Functional resonance analysis method (FRAM): FRAM, which is a qualitative approach, is employed for visualizing and modeling complex systems [20]. This particular method aids in the analysis of complex socio-technical systems and the revelation of the intricacy within everyday activities [21]. In addition, it provides valuable insights into the functionality of a process, thereby enhancing the foundational knowledge necessary for any qualitative or quantitative risk assessment. These insights are also used to introduce measures and strategies aimed at strengthening a system's capacity to achieve a heightened level of safety and resilience [22]. FRAM functions on the basis of a function-based approach. Functions serve to elucidate the daily functioning of a system [20]. The technological, human, and organizational functions associated with everyday operations form the foundation of a FRAM [18]. A central objective of FRAM is to identify a system's dynamics by exploring the interdependencies between functions [22].

The principles of FRAM emphasize the equality of success and failure in adapting to complexity, the ambiguity and predictability of socio-technical systems, the emergence of consequences from performance variability, and the potential for performance resonance to cause accidents. It highlights the importance of understanding variability and interactions within systems and the potential for unforeseen outcomes despite operational guidelines and rules [10, 23, 24].

To implement the FRAM method in the air separation unit, the following steps were taken:

First step: Identifying and describing the functions: The first step was to identify the necessary tasks of the system based on human, organizational, and technical functions. The goal was to describe in detail how to perform the work as a daily activity. Functions in FRAM are defined as what should be done to achieve a specific goal [10, 25-27]. After identifying the necessary functions, according to the organizational chart and with the cooperation and guidance of the expert panel members, we determined six basic aspects for each function. The aspects of each function included the following:

Input: input is traditionally defined as a function that is used or transformed by the function to produce output. Input can represent matter, energy, or information.

Output: something that is the result of the action. The output of a function is the result of what the function does; therefore, the output can represent matter, energy, or information (for example, an issued command or the result of a decision).

Preconditions: conditions that should exist before a function can be executed. In addition to providing a method by which functions can be coupled, the preconditions help find the functions necessary to complete a FRAM model.

Resources: what the function needs during execution (execution condition) or is consumed to produce output.

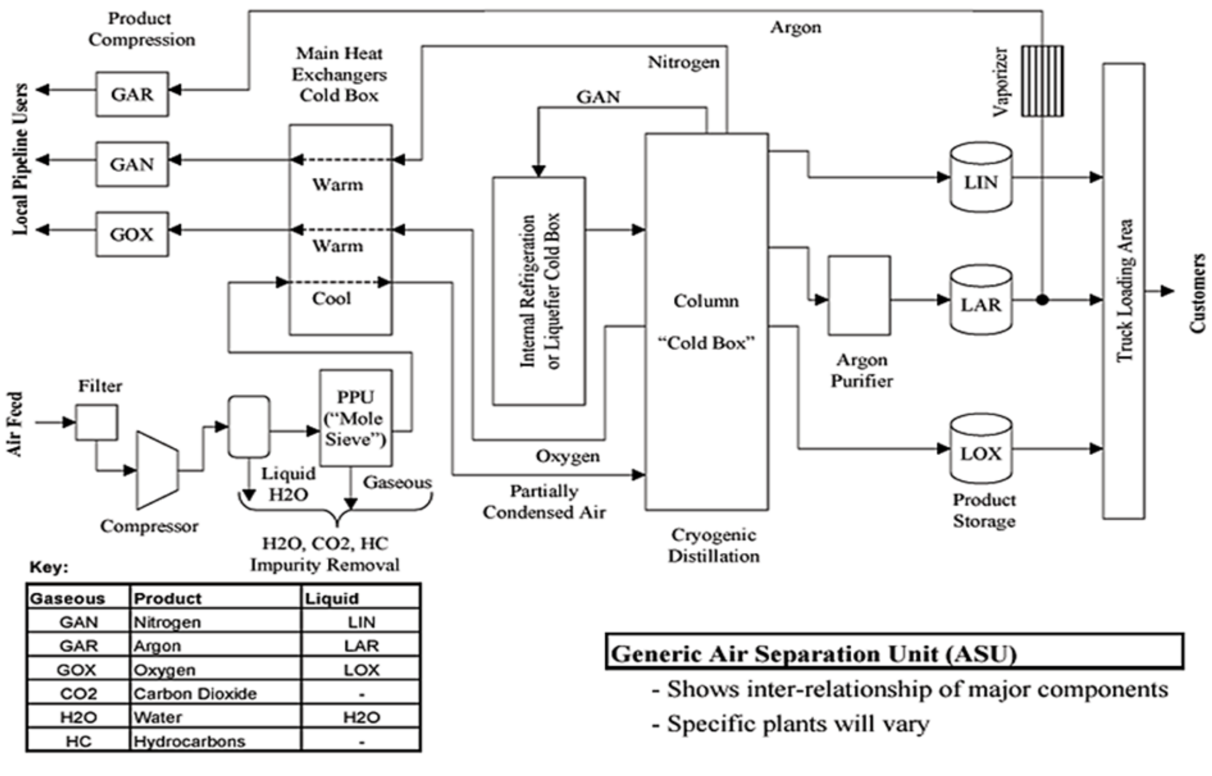

Fig. 2. Flow diagram of the air separation unit

Time: time constraints that affect performance (with respect to start time, end time, or duration).

Control: how to monitor or control performance. Control can be a program (algorithm), a method, or a set of instructions and procedures.

These aspects connect functions, and a socio-technical system is represented as a network of them [8]. Fig. 3 demonstrates the six basic aspects off each function.

Second step: Variability Identification: The purpose of the second step is to describe the variability of the functions that comprise the FRAM method [26]. In the FRAM method, a description of function variability is needed to understand how the functions are connected. There are three different reasons for the output variability of a function [10]. The variability of the output can be the result of the change in the performance itself. This can be considered a type of internal or endogenous variability. Production variability can be due to variations in the working environment, i.e., the conditions under which performance is performed. This can be considered a type of external or exogenous variability.

Output variability can ultimately be the result of the effects of the upstream function, where the output may vary from the upstream function (as an input, precondition, source, control or time). This type of interaction is the basis of performance resonance. It can also be called an upstream-downstream operational interaction. The variability of a function may, of course, be due to a combination of the above three conditions, i.e., internal variability, external variability, and upstream-downstream interaction [10].

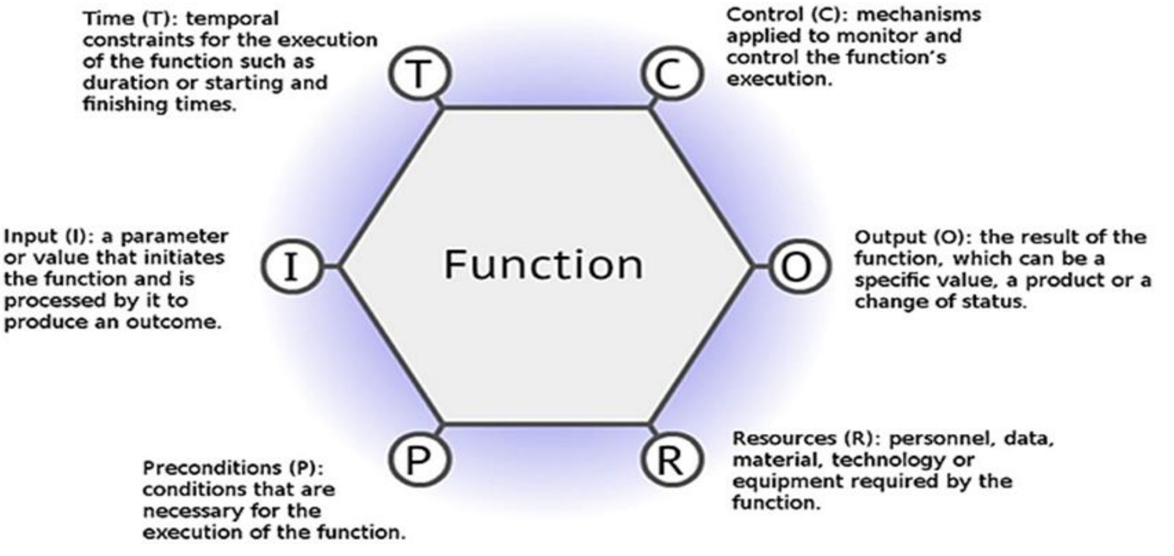

Fig. 3. Fundamental Elements of Functions within the FRAM Model.

One of the most common conventional methods to determine the potential variability depending on the environment is through the 11-item checklist of Common Performance Conditions (CPCs) among the functions [26, 28], which was performed in this study based on this method. The range of variability in CPCs is characterized by three options: "adequate", "inadequate", and "unpredictable". The more the number of "inadequate" and "unpredictable" options in examining a performance, the greater the variability in that performance, and as a result, the higher the risk will be. CPCs include the following:

- Resources availability: for sustainable performance, resources are necessary, and their lack leads to increased variability. Resources generally include people, equipment, and materials. These include human and technical functions.
- Education and experience: the quality of education along with operational experience shows that people are well prepared to deal with different conditions and consequences. This factor affects human performance.
- Communication quality: effective communication is another important issue related to timeliness and adequacy. This factor refers to technical (equipment and bandwidth), social, and human aspects.
- Human-machine interaction and effective support: in general, it refers to human-machine interactions, including intervention in design and various forms of operational support. Human-machine interaction has a significant impact on performance variability. This factor affects technical performance.
- Procedures and methods Accessibility: instruction and program variability (operational and emergency instructions) affects common response patterns. This factor influences training, experience, and human performance.
- Work conditions: this includes physical work conditions, such as ambient lighting, high brightness on surfaces, noise, temperature, and interruptions. Indeed, working conditions may range from favorable to disadvantageous, affecting technical and organizational performance.
- Goal number and conflict resolution: the number of responsibilities that a person undertakes must be in accordance with the principles and rules and not create contradictions. Clear rules for conflict resolution may significantly reduce variability. This factor affects human and organizational performance.
- Time pressure/time available: the time available to perform a task may depend on the interaction between the task as well as the dynamics of the process and execution. Lack of time, even subjectively, may increase performance variability. This factor affects human performance.
- Circadian rhythm/stress: it includes the 24-hour period of human biological activity. Lack of sleep or lack of coordination can reduce work performance. This, like the above, affects human performance.
- Crew collaboration quality: the quality of cooperation between personnel involves the interaction between formal and informal structures, and the level of trust and social conditions. This includes the impact of human resource management on people and their willingness to work. Similarly, this factor influences human performance.

- Quality and organizational support: role quality and team member's responsibility, safety culture, safety management systems, training and strategies for externally coordinated activities, and the role of external organizations, etc. are included in this section. This category affects organizational performance.

Third step: variability couplings: At this stage, the interaction of the functions with each other and with the human, organizational, and technical functions was investigated to determine whether there is a possibility of dependence/connection between the various tasks and functions [3, 25]. This dependence and connection occurs in the upstream-downstream functions, which can strengthen or weaken the function caused by them. For example, the output of a task may be an input to another task or the creation of a resource, precondition completion, control enhancement, or a time constraint [10].

Fourth step: variability monitoring and control: In this stage, the focus is on identifying the obstacles that either hinder or safeguard against the impact of an unwanted event. While FRAM determines whether variability may pose a risk, the protection objective aligns with the traditional approach to managing variability. In this framework, monitoring performance variability is of utmost importance [25].

Results

Based on the first step of the FRAM method, the necessary and important functions were identified with the help of a specialized team through interviews as well as studying the instructions and procedures of the air separation unit. The essential functions identified in the air separation process after the semi-structured interview are as follows.

F1. Training
F2. Preparation
F3. Air compression performance
F4. Cooling function (air washing and cooling)
F5. Purification function (impurity removal and moisture removal)
F6. Cooling function
F7. Fractional distillation and separation performance
F8. Performance of liquid and gas products
F9. Distribution and storage function
F10. PLC process

The six basic aspects of F5 as an example are descried in table 2.

Table 2. Six basic aspects of F5

Performance	Purification function (impurity removal and moisture removal)
Function	The cooled air from the outlet of the pre-cooling system goes to the dryers (vessel-absorption towers) to absorb impurities in the air, including moisture, carbon dioxide, and light hydrocarbons, including acetylene, which enter the purification section. The vessel consists of two substrates: the first substrate is used to absorb moisture by active alumina and the second substrate is used to absorb carbon dioxide and hydrocarbons by Molecursio.
Input	Cooled compressed air
Output	Purified compressed air
Precondition	-
Resources	-
Control	Plc process
Time	Plc process

In the second step, the CPC for each of the functions was completed by the expert panel, the results of which are given in table 3.

According to the expert team's statement, "air compression" function with 6 sufficient numbers, 4 insufficient numbers, and one unpredictable number, and "distribution and storage" function with 8 sufficient numbers and 3 insufficient numbers, revealed a high variability potential in the system. Although some functions have the same points as "distribution and storage" function, based on the evidence and interviews conducted, these functions have small potential for change. In the third step, the variabilities and identification of possible resonance between functions were drawn using the FRAM Model Visualiser (FMV) software. FMV software is a powerful tool designed to visualize and analyze the Functional Resonance Analysis Method (FRAM) model, providing insights into complex systems and processes. With its user-friendly interface and advanced analytical capabilities, FMV enables organizations to better understand and manage system performance and resilience.

The functions were entered in the FMV software, and the couplings were extracted using the results of interviews with the expert team based on the aspects of each function. Further, the modes that have the potential for resonance in the system were determined. Fig. 4 presents a graphic representation of these variability and couplings between functions. Resonance in functions is represented using the symbol . The analysis results indicated that the functions of "air compression" and "distribution storage", exhibited a high degree of resonance. Thus, these two functions have high variability, and the possibility of creating deviations as well as consequent accidents in these functions and tasks is higher.

During the fourth step of the FRAM, all barriers and control systems were identified at different stages, and suggestions were made to monitor performance variability. The objective was to detect any harmful variability and provide suggestions for implementing barriers. Table 3 serves as a reference for identifying the control systems or barriers that should be considered to mitigate the impact of potentially harmful variability.

Table 3. CPCs Checklist Results

Function	Rating category		
	Adequate	Inadequate	Unpredictable
F1	11	0	0
F2	11	0	0
F3	6	4	1
F4	9	1	1
F5	10	1	0
F6	8	2	1
F7	8	3	0
F8	8	3	0
F9	8	3	0
F10	10	1	0

Discussion

The first step of the Functional Resonance Analysis Method (FRAM) allowed the identification of essential functions within the air separation unit. Through a systematic approach involving interviews and a thorough study of instructions and procedures, a specialized team was able to pinpoint crucial functions that play a vital role in the operational integrity of the air separation process. The results of this study revealed ten essential functions. Each of these functions serves as a critical component in ensuring the smooth and efficient operation of the air separation unit.

The significance of these specific functions lies in their collective contribution to the overall functioning of the unit, underscoring the interdependent nature of the processes. The identification of these essential functions has substantial implications for the operational framework of air separation units. The authors would like to thank the research and technology deputy of the Shahid Beheshti University of Medical Science for the financial support of the research.In addition, it sheds light on the interconnectedness of these functions, emphasizing the need for cohesive integration and seamless interaction between the various operational aspects.

Furthermore, the recognition of these key functions serves as a foundational basis for enhancing safety protocols, refining operational strategies, and optimizing system reliability. By delineating these critical functions, the groundwork is laid for targeted improvements in training programs, maintenance procedures, and emergency protocols, ultimately bolstering the overall resilience of the air separation unit.

The results in Table 3 present the ratings for each function within the air separation unit across three categories: "adequate," "inadequate," and "unpredictable." These ratings indicate the perceived reliability and predictability of each function, providing valuable insights into the areas of strength and potential vulnerability within the operational framework. From the table, it is evident that functions F1 and F2 have received unanimous ratings of "adequate," signifying a high level of confidence in their reliability and predictability within the operational context. This underscores the robustness and consistency of these functions which effectively meet the established operational criteria. In contrast, functions F3, F4, F6, F7, F8, and F9 exhibit mixed ratings across the three categories, signaling varying degrees of reliability and predictability. Notably, while these functions are predominantly rated "adequate," there are instances of "inadequate" and "unpredictable" ratings, highlighting potential areas of concern and operational variability. This suggests the presence of certain operational vulnerabilities that warrant closer attention and targeted interventions to enhance their consistency and dependability.

Functions F5 and F10 manifest themselves as the most resilient functions when considering the evaluations, with an exceedingly positive appraisal of "adequate". This signifies notable degree of reliability and predictability, establishing these functions as firm foundations within the operational framework, fostering assurance in their consistent performance. The presence of "inadequate" and "unpredictable" ratings for specific functions underscores the imperative of proactive measures to address potential operational uncertainties and fortify the reliability of these functions. This may involve targeted interventions such as refining operational protocols, bolstering maintenance procedures, and integrating adaptive mechanisms to mitigate unpredictability and enhance operational resilience. Further, the variation in ratings across functions highlights the nuanced nature of the operational framework and emphasizing the need for a differentiated approach in addressing the specific requirements and challenges associated with each function. This underscores the importance of a comprehensive and tailored intervention strategy that accounts for the distinct operational dynamics inherent to each function.

In the “compression” function, the factor of working conditions due to high environmental noise, inappropriate environmental conditions, and the use of pressure level control gauges with non-ergonomic design can have a high potential variability or emerging risk. Environmental conditions can affect the organizational and technical functions of the system. The air compression function (F3) employs high-speed compressors that can generate heat and sometimes lead to explosions if not properly regulated. To regulate this function, a control solution is implemented by using compressor-specific Programmable Logic Controllers (PLCs) which can manage the number of times the system deviates from the parameters set by the compressor manufacturer. Furthermore, the Human-Machine Interface (HMI) and operational support in this function were deemed insufficient, which may negatively impact the technical function. Additionally, the high noise levels resulting from slow erosion in the equipment pose a potential risk to both the equipment and human. The combination of high stress levels, poor cooperation quality among individuals, and time constraints can have an adverse impact on both human and organizational factors, ultimately leading to a heightened potential for variability in this function. Although the potential variability of the cooling function (F4) is deemed insignificant compared to other system functions, one of its inputs is sourced from the air compression function, which has been identified as having high variability. By implementing ongoing monitoring and conducting field investigations, the performance resonance can be minimized. This function exhibits positive variations on its own, and the factors that contribute to favorable conditions should be reinforced. The cooling function is susceptible to partial variability which can be caused by time constraints, insufficient man-machine interaction (which can negatively impact the technical performance of the system), and inadequate circadian rhythms (which can negatively affect human performance).

Within the fractional distillation function (F7), factors such as inadequate training and competence, stress, circadian rhythm, and time pressure have an impact on the human factors of the system, which can introduce variability and associated risks to this function. As a result, the output generated by this function serves as an input for the gas and liquid production function (F8). Based on the investigations, the factors contributing to variability in this function include stress, circadian rhythm, time pressure, and inappropriate working conditions. If this function is linked to another function, it can introduce variability, which can cause resonance in the system and ultimately result in an accident.

The distribution and storage function (F9) with 8 adequate and 3 inadequate cases has variability potential. This potential can be attributed to unfavorable working conditions resulting from the storage of a large volume of liquid in tanks, which increases the risk of inadvertent leakage of cold liquid into the environment. Gas leakage and exposure to gas are among the factors that can impact both human and technical factors.

Based on interviews and the CPC checklist, the training and preparation functions (F1, F2) have been identified as having low and insignificant variability potential. Thus, these functions are not likely to introduce variability when interfacing with other system functions.

According to the expert team, the training function can have the most significant impact on generating positive variability in the process.

Based on the results in Table 3, it appears that the primary focus is on ensuring that expert and experienced operators are involved in the operations. The emphasis on accurate and real-time checks, monitoring, and compliance with standards is notable across various functions. The use of advanced automation systems and precision instruments is also highlighted in relation to PLC. It is evident that many functions listed require a high degree of precision and real-time monitoring. For example, functions such as air compression, cooling, purification, and fractional distillation require accurate and instant checks of pressure, temperature, and product quality. Additionally, the importance of expert operators is highlighted in several processes. The use of trained personnel and expertise is repeatedly stressed, indicating the critical role of human knowledge and experience in these operations. Furthermore, the emphasis on compliance with standards is notable, as observed in the detailed examination of product quality, adherence to work hierarchy in cooling processes, and monitoring of hardware and software activities in PLC systems.

Regarding the comparison of the results of this study with other studies, it can be stated that risk assessment using the FRAM method has been done very sparsely in the country, with one example breing the study of Shirali et al. in 2013. Its results indicated that the FRAM model is very useful and practical for understanding non-linear and dynamic states caused by the phenomenon of resonance among tasks in socio-technical systems to prevent accidents [23]. Also, in Alboghobeish and Shirali's study in 2022, potential variability (emerging risks), possible dependencies/couplings, and barriers used to reduce this variability were evaluated using the FRAM method. Then, the AHP method was employed to prioritize different functions. The results of FRAM modeling revealed that there was a possibility of high variability in five functions; these functions should receive special attention in order not to cause deviations in the system [29].

Regarding foreign studies, it is possible to refer to the study by Alberi et al. in 2016, whose results indicated that the findings of risk analysis using the FRAM method can contribute to a deeper understanding and learning of system performance in management of change [10]. In 2015, Rosa et al. utilized the FRAM method in a study with the objective of illustrating how performance couplings can combine to create an occupational hazard as a result of performance variability, as opposed to failure or inadequate performance [30]. In a study conducted in 2020 by Salehi et al. to explore the shortcomings of FRAM, it was shown that the use of additional methods to enhance the analytical and computational capacity of this method can help risk analysts and safety managers in complex socio-technical systems [20]. Josué E et al. (2022) used FRAM to monitor features in steel plate processing. These results revealed that the expert's attention features represented by the FRAM model structure are essential to the adaptive skill to manage variability in the working environment. This research contributes to elucidating the process of demonstrating adaptive skills in the manufacturing industry [31].

Elsewhere, Gattola et al. (2018) utilized the Functional Resonance Analysis Method (FRAM) to analyze socio-technical safety-related issues in manufacturing. A detailed case study related to forging operations was conducted to clarify the outcomes of the proposed method and identify mitigating actions to reduce risks and boost system resilience. The study highlighted the importance of considering both technical and human factors in managing risk and safety in large-scale industrial processes. It emphasized the need for a socio-technical perspective, where the role of humans in automated activities is recognized and studied. By analyzing the couplings and variability in the forging operations, the study identified the most critical couplings that require high adaptation and suggested measures to improve system performance and safety [32].

Table 4. Barriers and Control Systems

Function	Controlling systems or barriers
Training	Identifying training needs
	Planning and developing an educational program
	Using experts to conduct training courses
Preparation	Applying expert and experienced operators
	Accurate and real-time checking of pressure
Air compression	Applying expert and experienced operators
	Accurate and real-time monitoring of pressure
Cooling (air washing and cooling)	Compliance with the work hierarchy
	Accurate and instant temperature check
	Applying expert and experienced operators
Purification	Removal of moisture, carbon dioxide, and light hydrocarbons
	Employing suitable absorbent materials
Cooling	Accurate and instant temperature check
	Monitoring and checking the operation of the distillation tower
	Using proper insulation (Perlite)
fractional distillation and separation	Accurate and instant temperature check
	Considering standard instructions
	Detailed examination of product quality
liquid and gas products	Checking the purity of the material
	Monitoring the evaporation process
	Checking the performance of the compressor
Distribution and storage	Determining the consumption of each unit
	Accurate checking of the pressure and flow rates
	Providing the required pressure for each unit
	Monitoring the condition of materials stored in the tanks
PLC	Applying expert and experienced operators
	Monitoring all hardware activities
	Monitoring all software activities
	Using advanced automation systems and precision instruments

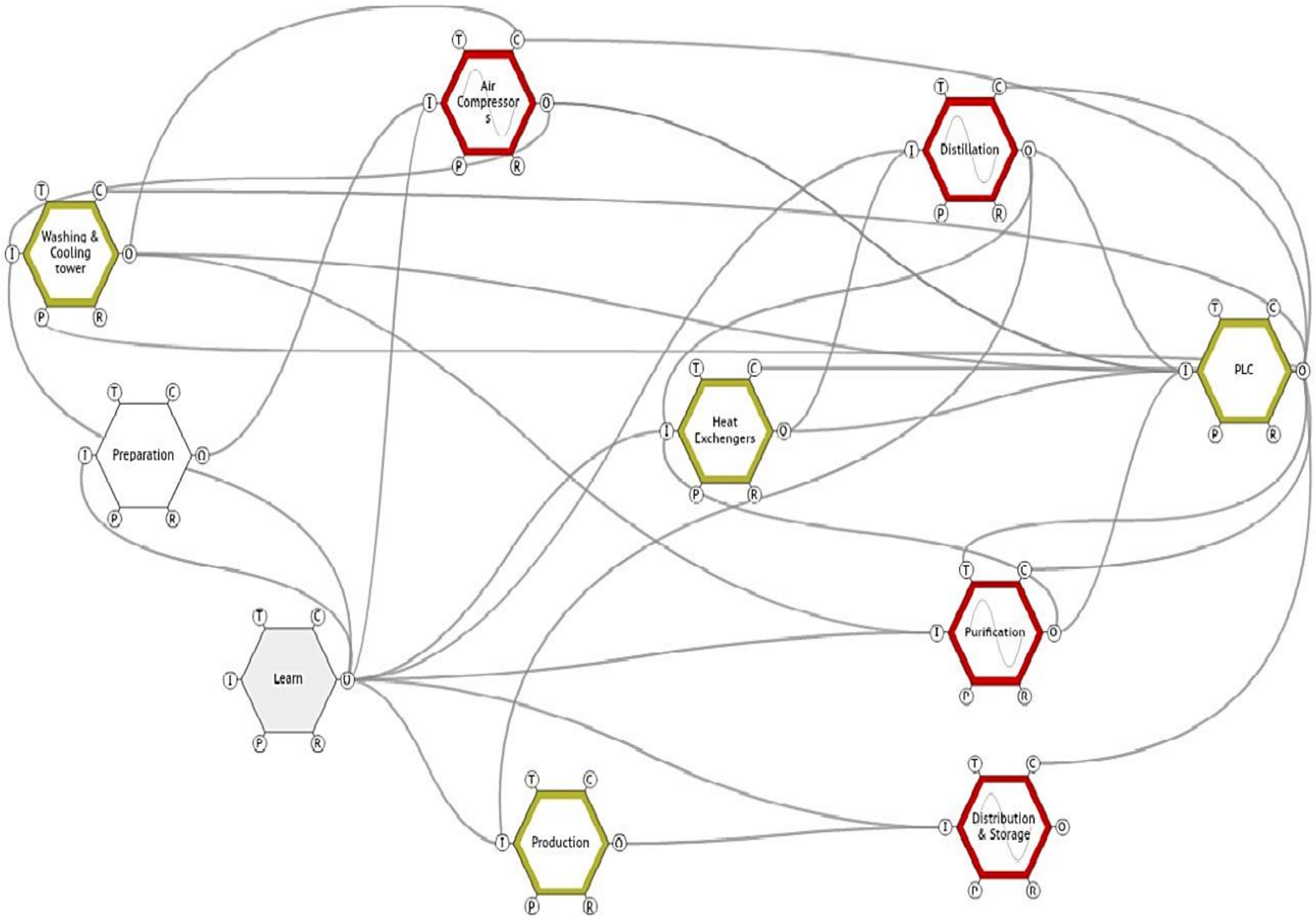

Fig. 4. Functions variabilities and coupling

Complex socio-technical systems, made up of human, technical, and organizational factors, are dynamic, making them unpredictable and potentially hazardous. Traditional analysis approaches fall short because of system complexities and rapid technological developments. The Functional Resonance Analysis Method (FRAM) is presented as a more innovative solution that supplements existing analysis methods rather than replacing them. The strength of FRAM is its ability to recognize and analyze dynamic relationships within the system, including the prediction of performance variability outcomes. The application of FRAM in identifying essential functions within the air separation unit has provided valuable insights into the interdependent nature of operational processes. Identifying and understanding these functions serves as a foundation for enhancing safety, operational strategies, and system reliability, while also providing a comprehensive understanding of the core functionalities necessary for effective unit operation. Furthermore, the detailed assessment of individual functions using the FRAM method and related risk assessment techniques has revealed potential areas of variability and risk, highlighting the need for targeted interventions to fortify reliability and safety within the system. The results accentuate the nuanced nature of operational dynamics and emphasize the importance of a tailored and differentiated intervention strategy to address specific challenges associated with each function. Comparatively, the study’s findings align with previous research involving FRAM, demonstrating the method’s efficacy in understanding non-linear and dynamic states in socio-technical systems, as well as its potential in contributing to a deeper understanding of system performance and resilience across diverse industries.

Conclusion

Collective insights underscore the importance of FRAM as a versatile tool for risk assessment and safety management in complex socio-technical systems. The method has been successfully applied to an air separation process unit, allowing for the identification of emerging risks and providing a more comprehensive, proactive approach to risk assessment. Despite its complexity and demanding nature, FRAM is highly effective for risk-prone, complex socio-technical systems.

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Conflict of interest

None declared.

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Ethical Considerations

According to the type of study, there is no need for special ethical considerations.

Code of Ethics

This study has been registered with the ethics code IR.SBMU.PHNS.REC.1400.173 at Shaheed Beheshti University of Medical Sciences

Authors' Contributions

Ali Alboghobeish: Formal Analysis, Investigation, Methodology, Visualization, Writing – Original Draft Preparation, Writing – Review & Editing. Hamid Reza Azimi: Data Curation, Formal Analysis, Investigation, Methodology, Visualization. Gholamabbas Shirali: Supervision. Mostafa Pouyakian: Conceptualization, Methodology, Project Administration, Supervision, Writing – Review & Editing.

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