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APPLYING THE FUNCTIONAL RESONANCE ANALYSIS METHOD FOR ASSESSING THE RISK OF WORK ACCIDENTS IN CONSTRUCTIONS SITES

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Abstract: *Construction is a high hazard industry that comprises a wide range of activities involving construction, alteration, and/or repair. Construction workers engage in many activities that may expose them to serious hazards, such as falling from rooftops, unguarded machinery, being struck by heavy construction equipment, electrocutions, silica dust, and asbestos. Worker' safety on construction sites is a global problem. The Functional Resonance Analysis Method (FRAM) is a safety analysis technique used to understand and manage risk in complex socio-technical systems, including constructions sites. It focuses on how seemingly minor variations in everyday work can resonate and combine to create unexpected hazards or even accidents. FRAM differs from traditional methods by modelling the dynamic and interconnected nature of systems, identifying potential emergent risks through functional variability and unexpected interactions. This paper aims, through a systematic literature review, to present the application of the Functional Resonance Analysis Method (FRAM) in the construction sites, thus contributing to increasing occupational safety and health on construction sites.*

Key words: *occupational safety, risk assessment, Functional Resonance Analysis Method.*

1. INTRODUCTION

Everywhere in the world the construction sector has high accident rates. In Europe, for example, over one fifth of deaths from occupational accidents occurred in the construction sector [1].

Worker' safety on construction sites is a global problem and there is a continuing need for improving safety management in construction. Until recently, construction safety was based, like many other industrial sectors, on linear models of causality [2]. Unfortunately, these models no longer fit the increasingly complex realities of organizations, which have now become complex socio-technical systems [3].

Problem description. In the case of simple systems, we can understand and explain their functioning through the cause-effect relationship. In the same way, we can understand and explain risks through the cause-effect chain that is triggered by the failure of a component. The situation changes in the case of complex systems, like a construction site, where it is difficult to predict how events and conditions may combine, leaving many risks undiscovered. In the case of these complex systems, the cause-effect approach is no longer helpful [4].

Also, complex systems cannot be meaningfully broken down into fixed, natural components. Their function is not simply a matter of success or failure; instead, everyday performance is inherently variable and must be flexible to adapt to changing conditions [5]. Outcomes result from the interactions between system elements, not from isolated causes. While some adverse events may be due to clear failures or malfunctions, many arise from the combination of normal performance variations. Therefore, risk and safety assessments should account for this performance variability, as it plays a key role in shaping both successful and adverse outcomes [6].

The Functional Resonance Analysis Method (FRAM) is a suitable tool for analyzing how variability propagates within a system [7]. More specifically, the method allows the investigation of mechanisms by which, through approximate adjustments, variability can be reduced, maintained within acceptable performance limits. FRAM-based approaches aim to provide a faithful representation of the real functioning of the system, with the aim of increasing its capacity to cope with unforeseen conditions, without exceeding the admissible limits of variability [8]. In this approach, complex systems are defined in terms of the functions and tasks they perform to achieve a given objective, and not according to their structure or the individual components that make them up. [9].

Research question: what are the application of FRAM in the construction sites?

2. METHODOLOGY

For the literature review we used the four steps of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework: *identification, screening, eligibility, included* (fig.1) [10].

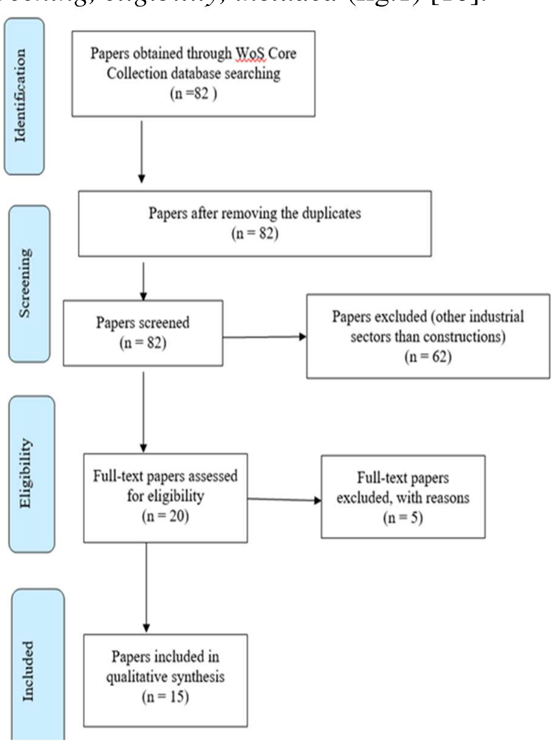

Fig. 1 PRISMA flow diagram

Searches in the identification step were made using the keywords "functional resonance analysis" OR "functional resonance" OR "functional resonance analysis method" AND "FRAM" across Web of Science database and returned 82 papers (fig.1). The Web of Science Categories to which these studies belong are as follows: Construction Building Technology, Engineering Civil, Materials Science Multidisciplinary, Engineering Industrial, Environmental Sciences, Geosciences Multidisciplinary, Geography Physical. 13.4% of papers belongs in the Construction Building Technology category, 13.4% to Engineering Civil category, 12.1% to Materials Science Multidisciplinary category, 8.5% to Engineering Industrial category (table 1).

Table 1

Record Count of Web of Science Categories.

Web of Science Categories	Record Count	% of 82
Construction Building Technology	11	13.415
Engineering Civil	11	13.415
Materials Science Multidisciplinary	10	12.195
Engineering Industrial	7	8.537
Environmental Sciences	6	7.317
Geosciences Multidisciplinary	5	6.098
Ecology	3	3.659
Engineering Chemical	3	3.659
Ergonomics	3	3.659
Geography	3	3.659
Computer Science Artificial Intelligence	2	2.439

The search timeframe was set at last ten years, 2016-2025. Figure 14 shows the number of published papers over time. The number of FRAM-related papers began to increase steadily starting in 2020, with a peak in 2024 (fig.2).

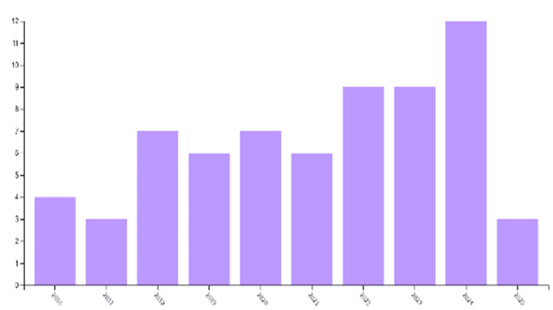

Fig. 2. The number of published papers over time

In the screening step, 82 papers were screened manually by reviewing titles and abstracts. 62 papers were excluded because they focused on FRAM in other industrial sectors than constructions, such aviation, healthcare, nuclear plants, agriculture. Also book chapters and theses were excluded.

The remaining 20 records were analysed in the eligibility phase. Five articles were excluded because they did not meet the inclusion criteria. The main reasons were the unavailability of the full text and the lack of an English version.

15 papers were included in the qualitative synthesis. From the literature included in the analysis, we observe a shift in the use of FRAM from accident investigation to the study of normal operations, „the study of what goes well”, a principle that derives from the Safety II paradigm. Out of 15 studies, only 3 report on the use of FRAM as a method for studying a work accident (table 2).

The first principle, the equivalence of successes and failures, it states that understanding how things go right in everyday work is just as important as understanding how and why they go wrong [12].

Table 2

Papers included in the qualitative synthesis.

Author	Year	Construction area	Instantiation Type	FRAM building methods	Type of research
Rosa, Lucio Villarinho	2016	Green building construction	Normal operation	Risk assessment	Qualitative
Furniss, Dominic	2016	Construction sector	Normal operation	Literature review Interview Case study	Qualitative
Toroody, Ahmad Bahoo	2016	Lifting structures deep offshore	Accident modelling	Risk assessment	Qualitative and quantitative analysis
Farrand, Luke	2019	Construction industry	Normal operation	Literature review Case study	Qualitative
María del Carmen Pardo-Ferreiraa	2020	Concrete structures	Normal operation	Analysis of available documentation, on-site interviews and observations	Qualitative
Kjartan Jørnsen	2020	Construction sites	Normal operation	Literature review	Qualitative
Akinlolu Maria	2020	Construction industry	Normal operation	Literature review	Qualitative
Ali Alboghobeish	2022	Construction process of a water reservoir	Normal operation	Risk assessment Case study	Qualitative
McCormack	2022	Construction sites	Normal operation	Risk assessment	Qualitative and quantitative analysis
Salmon, P. M.	2022	Construction sector	Modelling of accident causation	Literature review Interview Case study	Qualitative
Jue Li	2023	Large-scale infrastructure construction project	Multiteam coordination	Literature review, interview, observation, case studies	Qualitative
Tierra-Arévalo	2023	Construction sector	Normal operation	Literature review	Qualitative
Jianjun She	2024	Underground constructions	Deep foundation pit collapse accident	Accident report review	Qualitative and quantitative analysis
Zihao Guo	2024	Building constructions	Scaffold collapse accident	Accident case study	Qualitative
Li, J	2025	Shield tunneling construction	Normal operation	Risk assessment Case study	Qualitative and quantitative analysis

The second principle concerns approximate adjustments. Human performance is influenced by internal and external factors. These include fatigue, stress, emotional states, attention span, workload, and time pressure. In some situations, organizational dysfunctions, such as poor communication or unclear instructions, can make it difficult to complete tasks. [13]. In complex work situations, workers often have to make their own decisions and adapt their actions to meet the demands of the job. This means they frequently need to balance being efficient with being thorough - a compromise referred to by Hollnagel as the Efficiency-Thoroughness Trade-Off (ETTO). These adjustments are a normal and necessary part of work, but they can also introduce variability into the system, which may affect outcomes in both positive and negative ways [14].

Emergence is the third principle [15]. Due to dynamic and nonlinear nature of interactions within complex systems, outcomes cannot be predicted solely by analysing individual components. Typically, small variations in performance are a normal part of system operations and do not compromise safety. Still, under certain external conditions, these variabilities may combine and amplify one another, potentially leading to unexpected and undesired outcomes.

Functional resonance is the fourth principle - variability is an inherent feature of everyday operations. While individual performance variations may be harmless on their own, their interaction and accumulation across different system functions can lead to resonance, potentially resulting in adverse outcomes [16].

FRAM consists in 4 steps and one preparatory faze (fig.3) [17].

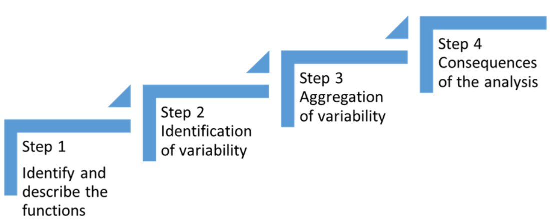

Fig. 3. Steps of the FRAM method

I In the preparation stage, the purpose of the modelling is established and the situation under analysis is described. This may concern an event that has occurred, in the form of an incident or accident, or a possible scenario for the future.

Step 1: In this stage the essential functions of the event are identified and each of them is characterized using the six basic aspects:

- Output,
- Input,
- Precondition,
- Resource,
- Control,
- Time.

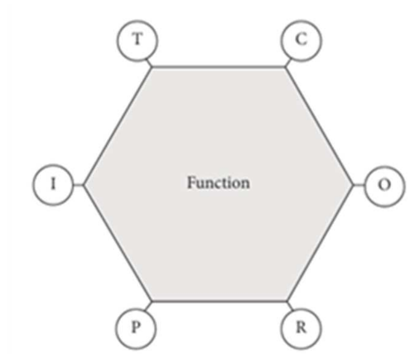

Fig. 4. FRAM hexagon: The six aspects used to characterize functions: input (I), output (O), preconditions (P), resources (R), control (C), and time (T) (adaptation from Holnagel) [18]

Step 2: In this stage, the final consolidation of the FRAM model is carried out, by verifying the description of all aspects related to the identified functions. Each aspect must be defined for at least two functions, so that the functional links and interdependence mechanisms within the analysed system can be highlighted.

Step 3: In this stage, both the actual and potential variability of the "foreground" functions and the "background" functions, which define the operational context, is analysed. The way in which these variations can influence the conduct of activities and the performance of the system is evaluated. Based on the existing or possible dependency relationships between the functions, the functional resonance mechanisms are identified, highlighting how the interactions between the individual variations can lead to the amplification of the effects and the emergence of critical situations in the analysed system.

Step 4: In this stage, measures are proposed to monitor and reduce performance variability, using indicators, barriers and system design or modification solutions. From our literature review we extracted some examples:

- Optimizing occupational health and safety plans to support resilient performance [19].
- Strengthening the culture of organizational safety [20].
- Detailed analysis of the process of decision making and activities of workers [21].

FRAM analysis can be initiated from any function of the system. During the modelling, it is usually necessary to include additional functions interconnected by coupling relationships. There is no single accepted level of detail. FRAM models typically include functions described at different levels of complexity.

4. APPLYING FRAM ON CONSTRUCTION SITES

This section reviews the studies included in the review. The aim is to clarify the areas of application of the FRAM method. The types of systems, contexts and situations analysed to date are reviewed. At the same time, the potential of the method to support the understanding of construction safety events is assessed. Of course, here is a concise, academic-style, and original restatement:

FRAM research in the construction field is predominantly qualitative. A total of 11 studies (73.3%) used qualitative methods. Only 4 studies (26.7%) applied quantitative methods. The construction of FRAM networks and the analysis of the differences between “the way work as imagined” and “the way work was done” relied on several data sources. The most common were the specialized literature, previous accident reports, and operational documentation. Direct observations, workshops, and interviews were also used. Interview participants included construction workers, foremen, site supervisors, project managers, and occupational health and safety personnel.

Only 4 (26,7%) of the reviewed papers attempted to quantify FRAM.

In recent years, through the lens of Safety II, the focus has shifted from analysing work accidents and identifying potential malfunctions (4 studies) to understanding what went well (11 studies).

A multidisciplinary team was formed on a green building construction site. It included construction specialists, environmental experts and worker representatives. The team applied the FRAM method to the reuse of construction waste at the crusher level. The process was selected because the concrete from the demolition was reused as a base layer. The activity is highly polluting and involves significant occupational risks. These include noise, vibration, dust exposure, thermal overload, forced postures and the risk of accidents. The analysis of resonant links highlighted the need for precise levelling of the equipment to ensure efficient system performance. Correct levelling leads to reduced energy consumption, reduced noise, limited dispersion of pollutants and increased productivity. At the same time, it contributes to improving worker safety. Excessive variability in levelling can affect loading and unloading operations. This can generate unstable working conditions and uncontrolled situations. In the analysed case, the solution to limit the functional resonance consisted in the modernization of the crusher. The modification included an anchoring system and an automatic control mechanism, with a role in reducing the variability of the levelling function.

Another study using the FRAM method for construction of concrete structures highlighted several relevant aspects.

- Concrete delivery and crane operations were identified as critical factors due to their impact on variability.
- Key performance indicators oriented towards current activity are used to a limited extent.
- The occupational health and safety plan is rarely applied in practice.
- Safety is influenced by organizational pressure.

Other research has proposed solutions for monitoring and reducing performance variability. These solutions aim at using indicators, implementing barriers and optimizing design or processes. A first step is to update occupational health and safety plans, which play a role in supporting resilient performance. Another important aspect is to strengthen the organizational safety culture. It is also recommended to analyse in detail the decision-making process and the current activity of crane operators, including determining the moment of concrete reception. At the same time, the need to develop key indicators oriented towards monitoring daily work and successfully carried out operations is emphasized.

5. CONCLUSION

The present paper aimed to review existing studies to understand what are the application of FRAM in the construction sites. Our study introduced and described the emerging FRAM methodology, its methods, and steps.

While FRAM has been applied to various industrial sectors (e.g. aviation, healthcare), there are many other sectors, such constructions that are not fully explored from this point of view and that may benefit from FRAM analysis.

We identified in Web of Science Core Collection database 15 existing FRAM studies in construction sector from 2016 to 2025 and further analyzed them in order to add to our understanding of how, where, and in what systems FRAM has been used so far and its potential for understanding construction safety occurrences.

Our findings will assist users of the method to interpret the assumptions in the implementation of FRAM and evaluate recommendations for system improvements and also will improve occupational safety and health in a domain that is recognized for its challenges in this area.

The limitations of our study are due to the fact that the search was done in a single database.

Further research may address some obstacles that limit FRAM application in practice such as: the need for simplification of the methods for training in how to implement and interpret FRAM, consistency, data collection methods. Also, the scope of the FRAM analysis could be expanded, to cover broader systems and understand how components interact.

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Aplicarea metodei de analiză prin rezonanță funcțională pentru evaluarea riscului de accidente de muncă în șantierele de construcții

Rezumat: Construcțiile reprezintă o industrie cu risc ridicat, care cuprinde o gamă largă de activități care implică construcții, modificări și/sau reparații. Muncitorii din construcții desfășoară numeroase activități care îi pot expune la pericole grave, cum ar fi căderile de pe acoperișuri, utilizarea utilajelor neprotejate, lovirea de echipamente grele de construcții, electrocutarea, praful de silice și azbestul. Siguranța lucrătorilor pe șantierele de construcții este o problemă globală. Metoda de Analiză prin Rezonanță Funcțională (FRAM) este o tehnică de analiză a siguranței utilizată pentru a înțelege și gestiona riscurile în sistemele socio-tehnice complexe, inclusiv șantierele de construcții. Aceasta se concentrează pe modul în care variații aparent minore în munca de zi cu zi pot rezona și se pot combina pentru a crea pericole neașteptate sau chiar accidente. FRAM diferă de metodele tradiționale prin modelarea naturii dinamice și interconectate a sistemelor, identificarea riscurilor emergente potențiale prin variabilitatea funcțională și interacțiunile neașteptate. Această lucrare își propune, printr-o analiză sistematică a literaturii de specialitate, să prezinte aplicarea Metodei de Analiză prin Rezonanță Funcțională (FRAM) în șantierele de construcții, contribuind astfel la creșterea securității și sănătății în muncă pe șantierele de construcții.

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