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MODELING AND OPTIMIZING COMPLEX OPERATIONS IN SOCIO-TECHNICAL SYSTEMS USING THE FUNCTIONAL RESONANCE ANALYSIS METHOD

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Rio de Janeiro

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Doctoral thesis presented to the Environmental Engineering Program, Escola Politécnica & Escola de Química, from Universidade Federal do Rio de Janeiro, as part of the requirements for obtaining a Doctor of Science degree in Environmental Engineering.

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I dedicate this PhD thesis to my family, including my dear wife Debora, my son Oliver, and my daughter Eloah, that pervaded with me the enormous challenges in this way.

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RESUMO

DE SOUZA, Ivenio Teixeira. **Modelando e otimizando o processo de tomada de decisão em sistemas sociotécnicos complexos com base no método de análise de ressonância funcional.** Rio de Janeiro, 2023. Tese (Doutorado em Engenharia Ambiental), Programa de Engenharia Ambiental, Escola Politécnica & Escola de Química, Universidade Federal do Rio de Janeiro, 2023.

Esta tese de doutorado aborda o uso de FRAM para modelagem e gestão de sistemas sociotécnicos, enfatizando aplicações na manutenção predial e na reciclagem de materiais de construção. Este é um tópico de investigação relevante, uma vez que ainda existem algumas fraquezas no FRAM (por exemplo, é difícil obter insights a partir das representações gráficas do FRAM, e a maioria das aplicações não inclui qualquer quantificação das variabilidades das funções), e o potencial deste método ainda não foi totalmente explorado. O trabalho aqui apresentado envolve cinco propósitos específicos e distintos: i) melhorar a funcionalidade do FRAM, esclarecendo como as funções são acopladas; ii) desenvolver uma nova forma de quantificar os resultados do FRAM; iii) examinar como a modelagem FRAM revela práticas de segurança decorrentes do conhecimento dos trabalhadores; iv) examinar o papel do FRAM na investigação da macrocognição durante emergências; v) desenvolver uma metodologia baseada em FRAM para melhorar as especificações de requisitos de software no projeto de tecnologia da informação (TI) para sistemas complexos. Esta tese visa atingir os objetivos propostos no formato de periódicos e artigos de conferências apresentados na seção de apêndices. Cada estudo baseia-se na aplicação FRAM e produz contribuições práticas e teóricas para a compreensão da variabilidade no domínio abordado, tanto ajudando projetistas quanto gerentes a reconsiderar as operações planejadas, apoiando adaptações dinâmicas na ponta.

ABSTRACT

DE SOUZA, Ivenio Teixeira. **Modeling and optimizing complex operations in socio-technical systems using the functional resonance analysis method.** DSc. Thesis (Doctorate in Environmental Engineering), Environmental Engineering Program, Escola Politécnica & Escola de Química, Federal University of Rio de Janeiro, 2023.

This doctoral thesis addresses the use of FRAM for the modeling and management of socio-technical systems, emphasizing applications to building maintenance and the recycling of construction materials. This is a relevant research topic as there are still some weaknesses in FRAM (e.g., it is difficult to obtain insights from the FRAM graphical representations, and most applications do not include any quantification of the variabilities of functions), and the potential of this method has not yet been fully exploited. The work presented here entails five specific and distinct purposes: i) improving the FRAM's functionality by clarifying how the functions are coupled; ii) developing a novel way to quantify the FRAM outcomes; iii) examining how the FRAM modeling unveils safety practices stemming from workers' knowledge; iv) examining the role of FRAM for investigating the macro-cognition during emergencies; v) developing a FRAM-based methodology to improve the software requirements specifications in designing information technology (IT) for complex systems. This thesis targets achieving the proposed objectives in the format of journals and conference papers presented in the appendices section. Each study builds on the FRAM application and produces practical and theoretical contributions for understanding the variability in the addressed domain, both by helping designers and managers to reconsider planned operations by supporting dynamic adaptations at the sharp-end.

CONTENTS

1. Introduction

This introductory chapter contains the general research interest of this thesis. Firstly, an initial sub-section discusses the relevance of the study. Secondly, the research problem and the three research questions are described. Thirdly, sub-section 1.3 details the research objectives, followed by the presentation of the performance analysis of the study. Finally, the structure of the thesis is outlined.

1.1 Justification and relevance

Building maintenance is not traditionally studied as a complex system. However, in recent years, it has displayed characteristics of complexity such as unexpected variability, distributed information, intractability, and unforeseen shapes of safety risks (PILANAWITHANA et al., 2022). The inherent nature of building maintenance works creates a dynamic environment and complex organizational structure, which constantly exposes their workers to varying and unexpected safety risks such as the risk of falls, bruises, cuts, etc (AKANMU; OLAYIWOLA; OLATUNJI, 2020) and contributes to becoming maintenance more labor-intensive, and costly in their operational stages (ASMONE; CHEW, 2020). Organizational aspects, such as constant pressures for productivity, aligned with the growing application of new technologies (e.g., sophisticated air- conditioning systems, new automated systems, etc.), also increment the complexity of such activities (SOUZA et al., 2021). The nature of such activities requires effective organizational safety management strategies.

Therefore, such characteristics indicate the need for a holistic approach based on resilience engineering to understand the risk and safety issues of workers involved in building maintenance, according to the Safety-II perspective. Following this perspective, the purpose of safety management in such complex socio-technical system is to find ways to enhance the ability of organizations to be resilient. It implies the sense of how systems can recognize, adapt to, and absorb variations, changes, disturbances, and disruptions, also anticipate undesirable conditions, and thereby continue the operation (HOLLNAGEL; WOODS; LEVESON, 2006).

As Safety II sheds new light on methods and techniques traditionally used to assess and manage safety. Among these, the Functional Resonance Analysis Method (FRAM) (HOLLNAGEL, 2012) is the one that seems to be getting the most attention from the Resilience Engineering community in the past few years. It has been widely used to visualize complex systems' operations based on performance variability. In this thesis, we look closer into this method, in terms of exploring possibilities of extending their applicability. FRAM is the core methodology that will conduct the research and will contribute significantly to several studies presented in this thesis.

We believe a methodology encompassing the FRAM, the Fuzzy sets (ZADEH, 1965) – along with the application of other supporting concepts and techniques such as the resilience potentials and the macro-cognition theory (KLEIN et al., 2003) – provides a solid background to examine the functional mechanisms of variability, in pursuing modeling and optimizing complex operations along the several aspects that pervade the work in this domain, including distributed cognition, human-computer interfaces, response mechanisms and anticipation actions, ensuring safety and adequate performance in maintenance activities.

1.2 Research Problem and Research Questions

This doctoral thesis addresses the use of FRAM for the modeling and management of socio-technical systems, emphasizing applications to building maintenance and the recycling of construction materials. This is a relevant research topic as there are still some weaknesses in FRAM (e.g., it is difficult to obtain insights from the FRAM graphical representations, and most applications do not include any quantification of the variabilities of functions), and the potential of this method has not yet been fully exploited. Based on the research problem stated, the following research questions have been proposed:

RQ1: How to operationalize a FRAM-based methodology that can identify and analyze critical activities in complex socio-technical systems in order to satisfy the following design criteria:

- To model the realistic work (work-as-done) of the system
- To identify sources of variability in work processes
- To be used as a quantitative support tool to rank critical activities

RQ2: How the FRAM modeling contributes to identify factors for improving organizational resilience in complex socio-technical systems, considering the following premises:

- identify resilience abilities from the functional perspective of the system
- identify cognitive aspects that embrace the variability at the sharp end

RQ3: How does the FRAM modeling contribute to improve the design of information technologies for supporting work in complex socio-technical systems by enhancing the requirements specifications in order to enable the design of more adherent, robust, and resilient systems?

Figure 1 conceptually sketches the research activities conducted in this thesis. It shows how the three research questions have some straightforward relationships. Starting from a general application of FRAM, a first study was performed with the purpose of understanding the benefits and limitations of FRAM models in analyzing complex operations on socio-technical systems (RQ1, Article I). Subsequently, a method has been developed to identify critical activities from the analysis of FRAM models from a semi-quantitative perspective (RQ1, Article II). From research question 1, two different methodological paths have been explored: the first one aimed to propose ways for improving organizational resilience as a combination of empirical abilities and the four cornerstones of resilience (RQ2, Article III), and through examining contributions of macro-cognition during abnormal operations (RQ2, Article IV). The second one intended to develop a method to improve the design of information technologies by enhancing the requirements specifications, as a means of supporting work in complex socio-technical systems by providing the design of more adherent, robust, and resilient systems (RQ3, Article V).

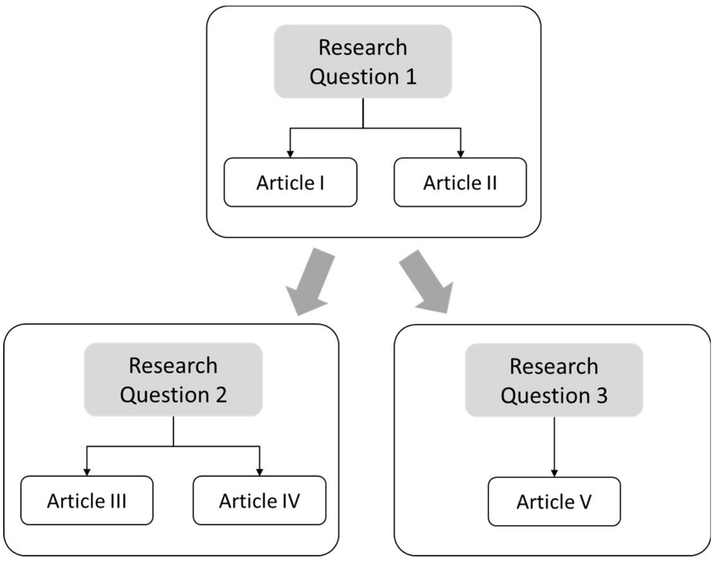

Figure 1 – Relationships among the three research questions addressed in the thesis

1.3 Objectives

The general objective of this thesis was to propose improvements to the traditional FRAM approach, including new analytical perspectives and strategies for making FRAM more user-friendly. To achieve the novelty of this study, five specific and distinct sub-objectives have been proposed. These sub-objectives are being organized in a sequence as follows:

1st Sub-objective: To identify the existing gaps in the FRAM applications and enhance their functionality by clarifying how the functions are coupled.

2nd Sub-objective: To develop a hybrid methodology that integrates the fuzzy sets theory into the FRAM structure to quantitatively estimate the criticality of functions.

3rd Sub-objective: To develop a methodological framework that strengthens safety practices stemming from workers' knowledge by integrating FRAM outcomes with the four cornerstones of resilience.

4th Sub-objective: To examine the role of FRAM in the investigation of macro-cognition in complex socio-technical systems during emergencies.

5th Sub-objective: To develop a FRAM-based methodology to improve the design of more robust and resilient information technology (IT) for complex systems by enhancing software requirements specifications.

1.4 Performance analysis of the study

This sub-section illustrates the development analysis of this work towards achieving the proposed sub-objectives presented in the previous sub-section. This thesis encompasses five scientific articles. Each one aimed at addressing a specific research question and objective, as illustrated in Table 1.1. Four of those articles have been published so far, thus the title is presented in the current section. Article IV is currently under review process.

Following a conceptual order, here are described the five appended articles integrating this PhD thesis. The full-length articles are included in the Appendices.

- Appendix 1 (Article I): "Modelling the work-as-done in the building maintenance using a layered FRAM: A case study on HVAC maintenance"
- Appendix 2 (Article II): "Soft computing for nonlinear method driven towards risk assessment of complex socio-technical systems"
- Appendix 3 (Article III): "Uncovering resilience abilities in maintenance teams for buildings with Functional Resonance Analysis Method"

- Appendix 4 (Article IV): "Resilient performance in building maintenance: a macro-cognition perspective during sudden breakdowns"
- Appendix 5 (Article V): "Information Technologies in Complex Socio-Technical Systems Based on Functional Variability: A Case Study on HVAC Maintenance Work Orders"

Table 1.1 – Connections between the research question, objectives, and articles of the thesis

Research Question	Research objectives and associated tasks	Article title
RQ1: How to operationalize a FRAM-based methodology that can identify and analyze critical activities in complex socio-technical systems?	• To model work activities during the maintenance of HVAC systems by the FRAM • To identify the existing gaps in the FRAM applications regarding the functionality • To examine how a layered FRAM model can decrease the complexity and the analyst's cognitive workload by clarifying how the functions are coupled	**Article I:** Modelling the work-as-done in the building maintenance using a layered FRAM: A Case Study on HVAC Maintenance
	• To develop a decision support system to rank critical functions in FRAM models • To integrate and test a soft computing approach into the FRAM based on fuzzy logic • To estimate the magnitude of variability for each upstream function • To estimate a dampening capacity for each downstream function	**Article II:** Soft computing for nonlinear method driven towards risk assessment of complex socio-technical systems
RQ2: How does the FRAM modeling contribute to identify factors for improving organizational resilience in complex socio-technical systems?	• To identify empirical resilience abilities in work activities during the maintenance of HVAC systems • To examine the adherence of the empirical resilience abilities to the four resilience potentials using questions inspired by the Resilience Analysis Grid	**Article III:** Uncovering resilience abilities in maintenance teams for buildings with Functional Resonance Analysis Method
	• To investigate the role of macro-cognition on resilient performance from the FRAM perspective • To model the system functioning during sudden breakdowns of HVAC systems using the FRAM • To examine how the macro-cognitive functions improve the	**Article IV:** Resilient Performance in building maintenance: a macro-cognition perspective during sudden breakdowns

	ability to anticipate and respond to emergencies	
RQ3: How does the FRAM modeling contribute to improve the design of information technologies for supporting work in complex socio-technical systems by enhancing the requirements specifications in order to enable the design of more adherent, robust, and resilient systems?	• To examine how variability modeling contributes to the requirements specification for the design and redesign of IT systems to support the work in complex socio-technical systems.	**Article V:** Information Technologies in Complex socio-technical Systems Based on Functional Variability: A Case Study on HVAC Maintenance Work Orders

1.5 Thesis organization

This first chapter presents the background and motivations that outlined this investigation. In addition, the aims and research questions were established. Chapter 2 illustrates the fundamental concepts that pervade this thesis. Chapter 3 contains an outline of the results obtained in this thesis. Chapter 4 concludes the thesis, presenting an appraisal of the main contributions, limitations, and suggestions for future research. Finally, appendices 1 to 5 consist of an assemblage of articles that were published (or under review) in a recognized international scientific journal or international conference. Consequently, each article has its specific title, methods, conclusions, and references.

2. Conceptual context

The next sub-sections illustrate the fundamental concepts that pervade this thesis. Firstly, the concept of complex socio-technical systems is presented. Subsequently, an overview of concepts of resilience engineering is shown.

2.1 Complexity in socio-technical systems

Socio-technical systems (EMERY; TRIST, 1960) refer to the interrelatedness of technological and organizational elements with their social elements that function to achieve specific goals (BAXTER; SOMMERVILLE, 2011). A socio-technical system consists of a dedicated structure in which social and technical elements influence one another, directly or indirectly to pursue a satisfactory functional performance (KLEIN, 2014). This concept regards the organizational aspect, i.e., organizational structures, work environment, policies, etc. The technical aspect is represented by technological artifacts (machines, tools, software, etc.) that enable performing a work. In turn, the social aspect refers to the human factor.

Complex systems are open systems that usually exhibit some interrelated attributes such as emergent behavior, many interacting parts, a large throughput of energy, information, or material, and adaptive behavior (WALKER et al., 2010). In such systems there is no immediately apparent relationship between cause and effect, and a structural decomposition becomes ineffective once the emergent functions are only present in the whole (RASMUSSEN, 1997). Hence, it is difficult, if not impossible to reduce the number of parameters or characterizing variables without losing their essential functional properties (PAVARD; DUGDALE, 2006).

When examining Snowden’s (2007) delineation between complicated and complex systems, it becomes clear that complex is not a synonym for complicated. A system is named complicated if it is ultimately knowable, presenting many interfaces but static (e.g., aircraft system), while a complex system is never fully knowable, and it is impossible to render a complete description of its functioning. Pavard and Dugdale (2006) define four properties of complex systems:

- Non-determinism: even when system elements are well-known, it is nearly impossible to precisely anticipate system behavior.
- Limited functional decomposability: it is difficult, if not impossible, to study system properties by merely decomposing them into functional parts.

- Distributed nature of information and representation: some cognitive properties within the complex system cannot be assigned to a single agent. Rather, they are distributed among several agents.
- Emergence and self-organization: A system property is considered emergent if situations are unpredictable, i.e., it cannot be anticipated from knowing the system's components functioning.

2.2 Modern risk and safety management: Resilience Engineering

Resilience Engineering emerged from Cognitive Systems Engineering in the beginning of 2000 decade, as a way to better understand and manage safety in complex socio-technical systems and provides an alternative approach to dealing with system complexity to achieve success (HOLLNAGEL; WOODS; LEVESON, 2006). A key issue in the Resilience Engineering perspective emphasizes the performance variability and the ability of individuals and organizations to continuously adapt their everyday work to match the needs of operating scenarios to ensure that ‘everything goes right’ under varying conditions (HEDGE; JACKSON, 2022). Some of its contributions to the understanding, design, and management of complex socio-technical systems have been explored by Patriarca et al. (2018a).

A recent vision on safety (named Safety II) was theorized from applying the Resilience Engineering perspective to complex systems in understanding and managing safety, and it is defined as the ability to succeed under varying conditions (WAHL; KONGSVIK; ANTONSEN, 2020). This perspective focuses on how work is done, looking for the different ways people synchronize activities to resolve conflicts and achieve shared goals, by enabling people to dynamically balance objectives of both safety and productivity (PROVAN et al., 2020). It argues that humans play a significant role in safety management, once the human ability to adapt work to deal with varying conditions instead of strictly following operational rules could contribute to systems working correctly (LEE; YOON; CHUNG, 2019). Several properties prove to be crucial to understand how the system adapts and to what kinds of disturbances in the environment, such as (WOODS, 2006):

- buffering capacity: the size or kinds of disruptions the system can absorb or adapt to without a fundamental breakdown in performance or the system’s structure.
- flexibility versus stiffness: the system’s ability to restructure itself in response to external changes or pressures

- margin: how closely the system is currently operating relative to one or another kind of performance boundary.
- tolerance: how a system behaves near a boundary – whether the system gracefully degrades as stress/pressure increases, or collapses quickly when pressure exceeds adaptive capacity
- cross-scale interactions: the interaction between various criteria and scale in a system depends on influences from scales above and below.

This modern vision is complementary to the traditional view (named Safety I) and it encourages a greater emphasis on the aspects that contribute to normal performance (HARVEY; WATERSON; DAINTY, 2019). Safety II argues that traditional approaches usually adopted for risk and safety management in several domains do not reveal sufficient information to identify and control risks. Techniques and methods used by conventional approaches are typically based on hindsight knowledge, failure reporting, and historical data-based probabilities. In addition, they presume that things go wrong because of identifiable failures or malfunctions of technological components, and procedures, beyond the humans, acting alone or collectively (HOLLNAGEL; WEARS; BRAITHWAITE, 2015). This vision is most useful in a system consisting of purely technical elements (HAM, 2020), once assumes it is always possible to identify a linear dichotomic cause/effect relation (PATRIARCA et al., 2018b) and removing or weakening the causes of adverse outcomes can improve safety (HIROSE; SAWARAGI, 2020). However, the Safety I perspective becomes progressively insufficient to provide a complete and comprehensive representation for modern complex socio-technical systems due to the inherent complexity of the system itself. This stems from the fact that reality is complex, variable, and even unpredictable, and working conditions are rarely ideal (PARDO-FERREIRA et al., 2020). Such characteristics indicate that the respective approaches should not be used to improve safety in work environments where workers at the sharp end have established safety practices that pervade work activities themselves (SALDANHA et al., 2020).

3. Results and research contributions

The efforts for addressing each research question proposed in this thesis required using the FRAM methodology to investigate the impacts of variability on the outcomes of complex socio-technical systems. Additionally, it was examined how to outline the risk profile of the system and moved toward solutions for optimizing operations in such systems. The three research questions were unfolded in five sub-objectives, as presented in sub-section 1.3, and five FRAM-based articles were developed in order to achieve these sub-objectives clearly and consistently. The next sub-sections present a summary of all articles developed in this thesis.

3.1 Appendix 1: Modelling the work-as-done in the building maintenance using a layered FRAM: A case study on HVAC maintenance

The article presented in Appendix 1 aimed at promoting a deeper understanding of the system, considering deviations in agreement with the concept of local rationality since, in some circumstances, they become unavoidable and even necessary to deal with the complexity of everyday work. Likewise, exogenous factors like environmental and contextual elements were analyzed as contributing factors to the real outcomes of the system.

It is noticed that workers deal with downgraded sites in performing maintenance and the physical demands of the activity impose occupational risks on them. This scenario somehow increases the complexity of the work, once they need to deal with scarce resources, inadequate tools, and an insufficient team to cover all the buildings on the university campus. By contrast, it is observed that the variability of human performance can have an important role in coping with demands that complex socio-technical systems require daily, strengthening positive outcomes. The analysis results can support the design or re-design of maintenance processes that enhance its capability to maintain its desired performance even under adverse conditions.

Overall, it is concluded in Article I that the customized performance analysis method of this study appears to be a useful method and user-friendly, capable of modeling the functional components of building maintenance activities in a user-friendly way. In the end, this work proposed a way to reduce the complexity of FRAM analysis, since it simplifies the graphical visualization of the model and overcomes limitations associated with analyzing functions, their couplings, and outcomes. This approach relies on examining snapshots of upstream couplings to investigate ways, in which the system performance can remain in an acceptable regime or lead to adverse outcomes. Hence, it can be clarified that this appendix aimed to achieve the first sub-objective designed for this study.

3.2 Appendix 2: Soft computing for nonlinear method driven towards risk assessment of complex socio-technical systems

The article illustrated in Appendix 2 explored the possibility of empowering the decision-making process regarding risk assessment of complex systems. Starting from the resilience engineering perspective, in line with the FRAM, this article aimed at developing a method to systematically identify and analyze critical activities. A framework was proposed to integrate the fuzzy sets theory within the FRAM structure, developing a soft computing algorithm aiming to quantify the FRAM outcomes, while increasing the significance of the judgments, their replicability, and validity. The framework is applied in an illustrative case study, based upon the recycling process of construction waste, and with its use, first, the magnitude of variability (MV) of human and organizational functions is characterized and valued. Secondly, the dampening capacity (DC) has been explored to express the capability of the system, in a certain context, to minimize undesirable effects resulting from disturbances and uncontrolled variability. Furthermore, the proposed framework also adds a theoretical contribution to relate dampening capacity and system performance. Thus, a novel indicator – the Coupling Response Index (CRI_{ij}) – was proposed as a nonlinear combination of the MV and the DC, and it represents to which extent the system performance affects and is affected by the coupling variability. CRI indicates the response signal in a particular coupling among two functions. The behavior of the system arising from these nonlinear couplings can exhibit dampening rates that depend on the energy dissipation within the system, for instance through the buffering capacity, flexibility, margin, tolerance, and cross-scale interactions, as identified by Woods (2006). On the other hand, when a functional resonance emerges in the system the consequences may spread through tight couplings leading to an amplification of undesirable outcomes. The proposed framework in Article II is found to be useful to facilitate the process of identifying and assessing the risk profile of the system, by devising strategies to amplify the positive impacts of variabilities or to prevent, control, or mitigate the negative impacts of disturbances or uncontrolled variability. We believe the proposed method might apply to any complex socio-technical system, providing accurate treatment to data from subject matter experts (SME). If a system is heavily large and the network is highly complex, the proposed methodology in Article II can be a good starting point for more sophisticated analyses. Hence, it can be clarified that this appendix aimed to achieve the second sub-objective designed for this study.

3.3 Appendix 3: Uncovering resilience abilities in maintenance teams for buildings with Functional Resonance Analysis Method

The purpose of RQ2 entailed addressing new tools or methods for improving organizational resilience in complex socio-technical systems. Originating from Holling's 1973 research on ecology and behavior of ecological systems, resilience was first introduced to the academic literature as "a measure of the persistence of systems and their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables" definition (HOLLING, 1973). The concept of resilience has evolved considerably since Holling's original definition and many definitions of resilience currently exist, from the resilience of critical infrastructures, and socio-ecological systems to economic resilience (FRANCIS; BEKERA, 2014).

Based on these observations and in the context of socio-technical systems, the concept of resilience adopted in this thesis is "the intrinsic ability of a system to adjust its functioning prior to, during, or following events, and thereby sustain required operations under both expected and unexpected conditions" (HOLLNAGEL et al., 2011). As for the adopted definition and considering that a resilient organization can predict, deal with, recover, and learn from unanticipated threats, it is necessary to examine how the system produces resilience in everyday work.

Building maintenance comprises a complex and dynamic set of activities, in which following operational procedures is far from sufficient to provide safe and productive work. Thus, safety in maintenance operations is constructed as needed through manifestations of resilience, associated with the performance of the front-line workers, mainly due to adjustments for overcoming constraints in time and resources in everyday work. The four cornerstones of resilience may represent a variety of resilience abilities. Particularly, they address the system's ability to respond to events, monitor evolutions, anticipate threats and opportunities, and learn from past failures and successes.

To answer research question 2, the FRAM was evoked as a support method for analyzing and improving organizational resilience in complex socio-technical systems. Although FRAM has demonstrated its efficiencies in numerous applications, empirical evidence on how to make resilience visible in FRAM models appears to be scarce in the literature. An initial hypothesis derived from the current research question is that traditional FRAM cannot be completely suitable to show how actual functions develop resilience potentials. Therefore, in this study, a methodology was developed for analyzing the resilience of an organization, by using a set of questions inspired by the Resilience Analysis Grid (RAG) jointly with the FRAM analysis. The method suggests the four cornerstones must be tailored to the organization under study, by a specific set of questions, as indicated in the RAG.

In the work, the FRAM has been used to describe the system's functions, the variability analysis, and potential resonances. Starting from the variability analysis, a questionnaire related to four resilience cornerstones was applied aiming to elicit the potential for resilience. Some questions were adopted, such as do the technicians try to learn from successes (things that go right) as well as from failures (things that go wrong) during maintenance operations? Also, how do they cope with incomplete information? To check requirements on the WOs, sometimes the technicians deal with poor descriptions of the failure in air conditioning devices. However, technicians have developed resilient abilities to deal with the specific demands of their activities, making use of the variability positively. For example, they benefit from knowledge acquired from previous experiences for interpreting data in work orders even though the available information has a high degree of subjectivity (Learning). Moreover, they monitor the weather conditions to decide on the maintenance schedule (Monitoring). On several occasions, technicians need to issue work orders verbally on the site, since the IT system is particularly time-consuming and thus is unsuitable for unexpected turns of events (Responding). Hence, it can be clarified that this appendix aimed to achieve the third sub-objective designed for this study.

3.4 Appendix 4: Resilient performance in building maintenance: a macro-cognition perspective during sudden breakdowns

This study focused on investigating how organizations can adequately respond to what happens, and how to anticipate actions to deal with stressful situations, considering its normal functioning. For this purpose, another perspective based on FRAM analysis has been addressed to explain the role of macro-cognition in dealing with complexity in crisis situations. The FRAM steps were used to functionally map critical processes involved in maintenance operations during sudden breakdowns in air-conditioning devices for a large university campus in Brazil. Six macro-cognitive functions (sensemaking, expertise, adaptation/improvisation, communication, coordination, and collaboration) were examined for their impacts on responding and anticipating actions.

The significance of the approach lies in dynamic explorations of the variability and its propagation throughout the system, as well as how the macro-cognition can be used and enhanced to help workers produce successful outcomes. The output results of this work indicate that the expertise is the macro-cognitive function presenting more interactions. Thus, such characteristics make this function crucial to provide a repertoire of adaptive behaviors to create resilient performance. Likewise, functions related to teamwork (coordination, collaboration, and communication) are pivotal to the quick response to sudden breakdowns. Such functions are often used in the frontline to respond to emergency demands. Therefore, refining macro-cognitive functions is an optimal procedure to understand what factors improve the ability to anticipate, and respond to emergencies, making the system more resilient. For example, increasing the efficiency of communication channels between workers and occupants could greatly improve the team cognition process. The adaptation/improvisation function constitutes a fundamental ability to adequately respond to the multitude of scenarios in daily activities. The detailed analysis of maintenance activities shows that technicians have rich repertoires for dealing with unexpected situations. They present sophisticated mental models to solve problems in performing repair from cues extracted from the environment. In addition, the sensemaking function is useful for managing improvisations, preventing them from resonating in the system and leading to loss of control. Hence, it can be clarified that this appendix aimed to achieve the fourth sub-objective designed for this study.

3.5 Appendix 5: Information Technologies in Complex Socio-Technical Systems Based on Functional Variability: A Case Study on HVAC Maintenance Work Orders

Traditionally, the FRAM has been used to provide qualitative reflections on accident investigations and prospective analysis. This work, however, presents a different bias, i.e., it sheds light on understanding how functional variability affects the usability of IT systems, producing successful and unsuccessful outcomes. This study proposes a FRAM-based methodology to examine the possibility of enhancing the requirements specifications for information technologies design in order to offer more adherent, robust, and resilient support to the work in complex socio-technical systems. The usefulness of the proposed methodology was demonstrated through a case study in the issuance of work orders for the maintenance of HVAC systems. In improving the elicitation and specification of software requirements in situations with a high-cognitive workload, Software Engineering can benefit by using practices of human factors and ergonomics. These practices bring techniques to enhance the understanding of how people work "in the practice", which is defined as "work-as-done". This approach has been adopted to help developers design IT systems that make the work more resilient.

IT systems are useful tools in promoting the quality and productivity of activities in complex socio-technical environments, such as building maintenance. However, the systems commercially available are generic and usually do not cover all operational details, in which customizations or even new developments are required. In this sense, software development projects usually suffer from misunderstanding of client needs and desires, or unsuitable knowledge about the domain. This stems from the limitation of the current requirements elicitation techniques in correctly understanding the complexity involved in socio-technical systems. Therefore, there is a need for effective evaluations of IT to ensure that the system requirements meet the needs of users. In this domain, the peculiarities of each organization, and the complexity involved in the activity stand out as obstacles for embedding those technologies.

In the case study presented in this study, the FRAM has been used to initially understand the functional variability in the WOs issuance process, which comprises activity that requires an interface human-computer. Additionally, it explored whether such a strategy would be advantageous to re-design the IT system used by the maintenance team (called CISI) from the improvement of the process of requirements elicitation and specification. The results revealed that FRAM overcomes classical approaches such as Business Process Management and Notation (BPMN) to model activities and ultimately provide the necessary information to elicit software requirements. The main advantages rely on the fact that it enables the analyst to understand how the socio-technical system can vary in daily activities. Moreover, from the principle that functional variability is a systemic property, we believe that FRAM outcomes provide ways to specify software requirements that embrace the variability, instead of constraining it. Therefore, as couplings among functions are prone to present variability, understanding each one is important for capturing requirements in a better way. By contrast, as functional resonance concerns the combination of the internal variability of a function with the variability of another function with which it is coupled, the study also proposes a set of mitigating actions to be translated into software requirements driven to restrain potential resonance. Hence, it can be clarified that this appendix aimed to achieve the fourth sub-objective designed for this study.

4. Conclusion

The development and validation of this doctorate thesis are illustrated in the format of journal and conference publications. The study developed in this thesis was focused on how to use the FRAM for the modeling and management of socio-technical systems, emphasizing applications to building maintenance and the recycling of construction materials. The application of the FRAM provides guidance on variability management in complex socio-technical systems. The FRAM can address disturbances in complex socio-technical systems by investigating technological, human, and organizational aspects, and other exogenous factors affecting complex systems' performance. Despite several advantages for modeling complex systems, it was recognized that there are still some weaknesses in FRAM, e.g., it is difficult to obtain insights from the FRAM graphical representations. Moreover, it was acknowledged that most applications do not include any quantification of the variabilities of functions, and the potential of this method has not yet been fully exploited. This thesis attempted to answer three questions posed at the beginning of this work. The aim of this thesis was to propose improvements to the traditional FRAM approach, including new analytical perspectives and strategies for making FRAM more user-friendly.

4.1 Contributions

One of the main contributions of this thesis is that FRAM as a method can be steered towards different purposes within the universe of complex socio-technical systems. It may contribute to knowledge by providing a reference for researchers and practitioners interested in designing work systems based on resilience engineering. This work targets developing an alternative way to enhance the functionality of FRAM modeling by clarifying how the functions are coupled. A decision support system is proposed to quantitatively estimate the criticality of functions in FRAM models. Moreover, this work proposes a methodological framework aiming to identify safety practices stemming from workers' knowledge and a new perspective to examine the team macro-cognition and their impacts on performance during emergencies. Lastly, this work integrates the FRAM structure into the software engineering concepts to enhance the software requirements specifications to improve the design information technology for complex systems.

4.2 Limitations and future recommendations

This thesis proposes improvements to the traditional FRAM approach based on applications to building maintenance and the recycling of construction materials. However, some limitations of this thesis must be described. First, the small sample size of participants limits the generalizability of the findings of this study to other building maintenance activities. Therefore, in order to expand the generalizability of the results, future studies are required to consider alternative modalities of maintenance and include more diversity and number of participants, including maintenance technicians and customers. Moreover, further research could address the utility and applicability of the proposed methodology to analyze complex operations, considering different domains, with distinct complexity characteristics.

Second, the FRAM was combined with fuzzy sets to create a basis for estimating the criticality of functions that is explored by calculating the magnitude of variability and the dampening capacity. For reducing computational effort during the fuzzy inference implementation, it considered only two phenotypes of variability (timing and precision), disregarding other possible states of the quality of the function output (i.e., speed, distance, sequence, object, force, duration, and direction among others). Moreover, the current study supposes that subject matter experts (SMEs) have the same importance in computing their opinions to calculate the FRAM outcomes by using fuzzy sets. This was a reasonable approach to test the method, but it would be worthwhile in future works to merge the current approach with MCDM methods (e.g., AHP, TOPSIS, ELECTRE, PROMETHEE, etc.) that could be an effective way to evaluate the relevance of SME's. Future research could also concentrate on developing an integrated computational tool to facilitate the implementation of the quantitative FRAM, based on the proposed method. Third, in examining the role of macro-cognition in resilient performance, this thesis has addressed only six macro-cognitive functions, and others unexplored in the current study might be examined in further studies to understand their impact on decision-making and their role in the overall resilience of the system.

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Appendices

Appendix 1

Modelling the work-as-done in the building maintenance using a layered FRAM: A case study on HVAC maintenance

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Modelling the work-as-done in the building maintenance using a layered FRAM: A case study on HVAC maintenance

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ABSTRACT

Maintenance of heating, ventilation, and air-conditioning (HVAC) systems has become one of the most relevant maintenance operations in public buildings. The intense interaction among human agents and equipment, aligned with information's distributed nature, exposes the maintenance workers to significant and complex risks during their routines. Prescribed procedures frequently differ from reality, which becomes essential the examination of the work-as-done. The functional resonance analysis method (FRAM) offers a promising perspective on analysing work-as-done in daily activities. However, the FRAM brings a limitation due to its complexity of representation. This study presents a layered FRAM as an alternate way of analysing the work-as-done in the maintenance of HVAC systems. This approach consists of cutting the couplings among functions in those presenting variability to clarify how the functions affect each other. The results show that the layered FRAM offers a better view of functions, decreasing the complexity and the analyst's cognitive workload. This contribution is a user-friendly and straightforward technique to facilitate the model analysis and explore a new perspective to popularize and spread the FRAM to treat complex issues.

1. Introduction

Maintenance plays a pivotal role in operating buildings, reducing the impact of structural degradation, aiming to prolong the lifespan of the buildings (Khalid et al., 2019). The HVAC (Heating, ventilation, and air-conditioning) systems constitute crucial types of equipment in building infrastructure, as responsible for maintaining good indoor air quality through adequate ventilation with filtration and providing thermal comfort for the building's occupants (Antoniadou and Papadopoulos, 2017). Therefore, adequate maintenance is crucial to maintain HVAC systems running and prevent any hazardous failure that can bring risk to the building's occupants. However, the prevalent form of air conditioning maintenance in buildings is simply responding to complaint calls or apparent equipment failures (Gunay et al., 2019). Likewise, as noted in the current research, the maintenance strategy adopted is purely reactive. This strategy ignores scheduled maintenance once the user operates a component until it fails, then a repair or replacement is triggered (Ruparathna et al., 2018).

In complex socio-technical systems such as building maintenance (Souza et al., 2021), the activities written in procedures and guidelines, including unwritten rules, i.e., WAI: Work-As-Imagined (or more specifically as-prescribed), frequently fail to represent the realities of the work carried out in practice, i.e., WAD: Work-As-Done (or as-disclosed, as observed) (Moppett and Shorrock, 2018). In this sense, prescribed procedures cannot cope with everything that occurs in a complex workplace once they cannot fully provide effective and efficient ways to control and manage unexpected situations (De Carvalho et al., 2018). Furthermore, the building environment and the working conditions can all pose challenges to managing safety (Oswald et al., 2018). The workers are exposed to hazards difficult to measure, and the ever-changing workplaces may potentially affect all workers on the site (Rosa et al., 2015). The embedding of new tools and technologies in HVAC systems increases the complexity of maintenance tasks (Au-Yong et al., 2014; Liu et al., 2013).

Thus, it is essential to investigate the WAD in the maintenance activities to give insight into some of the contextual factors that affect

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Abstract

Maintenance of heating, ventilation, and air-conditioning (HVAC) systems has become one of the most relevant maintenance operations in public buildings. The intense interaction among human agents and equipment, aligned with the distributed nature of information exposes the maintenance workers to significant and complex risks during their routines. Prescribed procedures frequently differ from the reality, which become essential the examination of the work-as-done. The functional resonance analysis method (FRAM) offers a promising perspective on analysing work-as-done in daily activities. However, the FRAM brings a limitation due to its complexity of representation. This study presents a layered FRAM as an alternate way of analysing the work-as-done in the maintenance of HVAC systems. This approach consists of cutting the couplings among functions in those presenting variability to clarify how the functions affect each other. The results show that the layered FRAM offers a better view of functions, decreasing the complexity and the analyst's cognitive workload. This contribution is a user-friendly and straightforward technique aiming to facilitate the model analysis and explore a new perspective to popularize and spread the FRAM to treat complex issues.

Keywords: Green product; circular economy; energy conservation; FRAM; resilience engineering; maintenance; HVAC; work-as-done

Introduction

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Due to the continuous increase in the complexity of socio-technical systems, classical approaches, such as Root Cause Analysis (RCA), Fault Tree Analysis (FTA), Failure Mode and Effect Analysis (FMEA), etc. are no longer sufficient to provide a complete and comprehensive picture for the representation of a systemic perspective in the system's analysis (Slim and Nadeau, 2020). These methods believe that the system's structure and even its behaviour are stationary, i.e., do not change with time. Furthermore, they are often designed to break up the system into parts and evaluate each one separately (Hollnagel, 2012) to linearize even the workers' behaviour (Rosa et al., 2015). On the other hand, the whole system cannot be comprehensively understood by simply knowing its components or parts (Kaya et al., 2019).

Hence, new and robust methods, including an integrated view on technological, human, and organizational system components, are needed for improving the analysis and modelling of highly complex systems (Patriarca et al., 2017b). Which are characterized by being dynamic, incompletely described, and therefore underspecified (Hollnagel, 2012). Thus, for reliable analysis and a better understanding of these systems, applying a perspective in line with Resilience Engineering (RE) becomes necessary. It has gained attention and importance in fields that cope with complexity, unpredictability, and ever-changing scenarios that lead to threats and sometimes even danger (Pęciłło, 2016). RE approach concerns a new method for safety management that focuses on how systems anticipate undesirable conditions or managing changes, and thereby continue the operation, even after a disruptive event, or the presence of continuous stress (Hollnagel et al., 2006; Martinetti et al., 2019).

The functional resonance analysis method (FRAM) proposed by Hollnagel (2012) has been developed under the concepts and principles of the RE, providing a technique that analyses the nature of everyday activities. It focuses on the interactions among functions by modelling nonlinear dependencies, looking at their functional aspects instead of their physical structure (Patriarca et al., 2018), as well as showing the critical elements needed to build a safe and productive work environment. In addition, it supports the system analysis to identify the potential variability of each function and the arising emergent behaviours potentially relevant for the system's resilience (Bellini et al., 2020).

FRAM is a relatively new methodology and has recently been attracting consideration to many researchers all over the world with recent studies in several domains, such as aviation (Patriarca et al., 2019), construction (Pardo-Ferreira et al., 2020), manufacturing (Zheng et al., 2016), software engineering (Souza et al., 2021), environmental (Patriarca et al., 2017c), healthcare (Raben et al., 2017), oil and gas industry (França et al., 2020, 2019), maritime operations (Patriarca and Bergström, 2017), artisanal fishing (Saldanha et al., 2020) among others.

FRAM offers several benefits since it aims to avoid oversimplification and quantify ill-known variables, which could turn against its founding principles (Ferreira and Cañas, 2019). Also, FRAM is not based on a specific model of how work takes place, as most methods for work analysis, including risk and safety analyses. Instead, it is used to produce a model that describes the functions and their dependencies that together make up the system's performance (Clay-Williams et al., 2015). On the other hand, FRAM presents some disadvantages in its application in modelling complex socio-technical systems. One of these disadvantages comprises the difficulty in analysing variability in a system model with a large number of functions (Pardo-Ferreira et al., 2020) with many interacting agents and interconnected functions (Patriarca and Bergström, 2017) due to the inherent feature of the method, which presents an overwhelming complexity of graphical representation (Patriarca et al., 2018).

Some contributions from the literature have been addressed to improve the visualization of functions. For instance, when modelling the drug administration process in neonatal intensive care units (NICUs), Kaya et al. (2019) began to explore the idea of extracting information from the integral FRAM to improve the visualization of a subset of functions. In the same way, Saldanha et al. (2020) also used this strategy when representing a set of functions from the integral model in secondary graphics. However, these approaches do not encompass a systematic manner that establishes guidelines in applying this valuable way of visualizing them and their couplings.

Although some advances in the literature, building a FRAM model may become a difficult task, resulting in a complex model, leading to limited benefits for the analysis (Patriarca et al., 2017a). This paper aims to enhance the traditional FRAM approach through a novel technique to simplify the graphical complexity of the model and overcome limitations associated with analysing functions, their couplings, and outcomes. This technique is based on building a layered FRAM model to offer a better view of functions. In this technique, the lens is focused on the functions presenting variability. This novel approach aims to clarify the interactions among functions to investigate how inputs affect the outcome of a function. Also, this approach seeks to provide fewer analyst's cognitive efforts and, consequently, more accurate analyses. In order to illustrate how the technique works, a case in the domain of building maintenance is presented, especially the work analysis in the maintenance of HVAC systems in public buildings, indicating possible advantages and future developments.

The rest of this paper is organized as follows. First, section 2 presents the theoretical background of the FRAM and the proposed layered FRAM, followed by its application to a real-life case study in Section 3. Next, section 4 provides a discussion of the results. Finally, section 5 summarizes the conclusions of the study and provides suggestions for future research.

Methodologies

Functional Resonance Analysis Method (FRAM)

The FRAM is a systemic analysis method used to describe the activities of a complex socio-technical system. This method considers system performance's nonlinear nature rather than building a sequential cause-effect model of events over time (Ferreira and Cañas, 2019). The main purpose of the FRAM is to build a model of the functions of a system that describes how performance variability may occur in the work-as-done (WAD) and how the effects may spread through the system. FRAM helps understand the underlying dynamics of system functions, identifies critical couplings among functions, and offers several resources for managing variability (Patriarca and Bergström, 2017).

FRAM methodology is based on four principles (Hollnagel, 2012): First, the equivalence of successes and failures denotes that failures and successes occur in much the same way.

Second, the principle of approximate adjustments preaches that workers typically adjust their performance to overcome disruptions at the workplace due to the impossibility of prescribing tasks and procedures in detail. Therefore, the performance must become flexible rather than rigid. If workers always adhere to prescribed guidelines, the number of accidents and incidents would be much higher in unexpected events. Third, the principle of emergence relates that some occurrences at work are difficult to predict. These occurrences may lead to results that cannot be explained just by a cause-effect relationship of the operation of specific components or parts. Finally, the fourth principle states that the variability of some functions may sometimes combine, i.e., they may mutually affect each other, leading to either positive or negative outcomes. These outcomes are difficult prognoses and significant uncomfortable management.

Therefore, a novel enhancement needs to be addressed to undertake the existing approach's limitations concerning the graphical representation. This study proposes building a layered FRAM through cutting links among functions from the integral FRAM model. The significance of this technique lies in supporting the analyst during analysis with FRAM.

Layered FRAM with the cutting technique

Four steps are necessary to follow to build a FRAM model, which is considered the original structure of the FRAM, including a sub-step on the traditional approach.

Step 1 – Identification and description of functions

This step engages in identifying and describing the essential functions to perform the activity. In the FRAM model, the functions represent the everyday work, including activities from individuals, equipment, or group of individuals. As illustrated in Figure 1, a function comprises six aspects at the hexagon's corners.

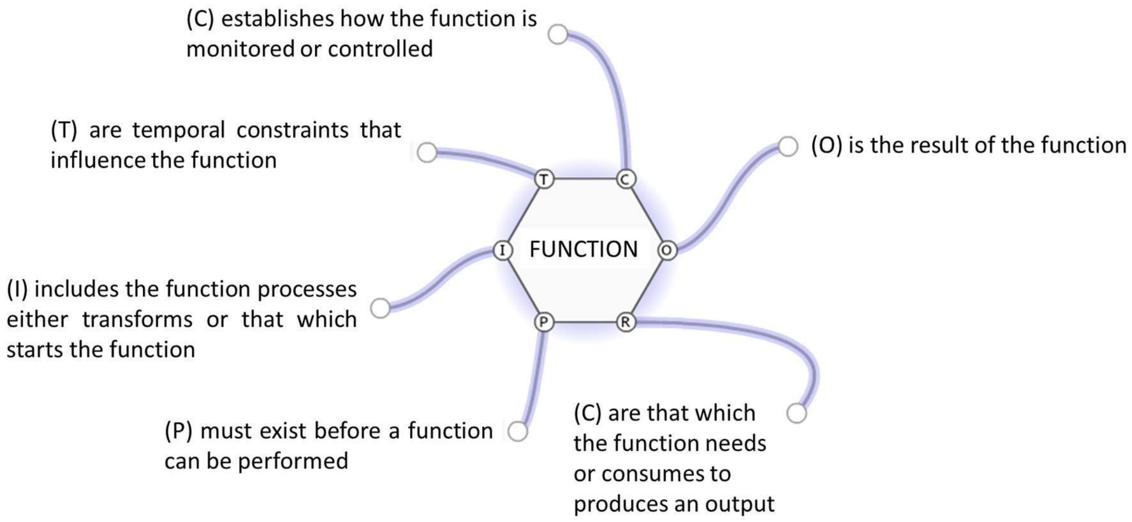

Figure 1: Description of aspects in the function

Step 2 – Identification of variability

A second step for modelling is identifying the output variability of each function of the model, characterizing each function with its potential and actual performance variability. The variability related to the outputs is described using multiple phenotypes: in terms of time/duration (i.e., too early, too late, omission), force/distance/direction (i.e., too weak or insufficient, too strong), wrong object, and sequence (i.e., omission, repetition, jumping). On the other hand, a simple approach considering two phenotypes in terms of timing (i.e., too early, too late, on time, not at all) and precision (i.e., imprecise, acceptable, precise) is available to model a system. This study will evaluate the simple configuration, only identifying time and precision as phenotypes as they are enough to describe most outcomes.

Step 2.1 – Analysis of functions with the cutting technique

As previously stated, a large number of couplings among functions generate a considerable amount of possible paths for the spreading of variability, becoming a complicated network to analyse (Pardo-Ferreira et al., 2020) due to the lack of understanding of the graphic representation, which can generate an incomplete and fault analysis. In this step, several cuts are introduced in the couplings of functions presenting variability. The technique consists of cutting couplings of a function or subset of functions and represents this cutting as a secondary layer from the integral FRAM model.

Once the functions presenting variability and their couplings are defined, it is possible to examine how coupling variability affects those functions' purposes and objectives to be achieved. In order to make the analysis more appropriate, no more than two functions are analysed simultaneously.

Step 3 – Aggregation of variability

This step takes advantage of analysis from Step 2.1 for investigating the functional resonance resulting from the combination of variability. Especially for human and organizational functions, the variability concerns smooth adjustments that aim to deal with complexity and disturbances in the workplace. Although these adjustments are mainly well intended to ensure safe and reliable deliveries, the outcomes of such adjustments can justify why things go wrong (Bjerga et al., 2016). Thus, this third step aims to examine realistic scenarios, called instantiations of the model, to understand how the potential variability of each function can spreads through the entire system, leading to undesirable outcomes.

Step 4 – Management of variability

The fourth and last step in the application of FRAM is the monitoring and managing of the performance variability. To produce better outcomes in this step, Hollnagel (2012) proposes that the most fruitful strategy proposes actions to damping adverse effects, eliminating those that can lead to undesirable results, and, conversely, recommend measures to enhance positive effects without losing control of the activities.

Research setting

This section aims to explore the potential of applying the proposed technique to improve analysing the coupling among functions in a FRAM model. A cross-sectional study was conducted in a department for building maintenance (DBM) of a public university in Brazil.

Description of field study

The field of this study is a university campus in Rio de Janeiro, Brazil. The university comprises thirteen graduate programs in engineering, 131 laboratories, 346 professors, and 457 employees. The organizational structure includes the DBM, which is responsible for maintaining the operational capacity of the company's infrastructure. The DBM comprises six maintenance domains: Electrical, plumbing, HVAC, civil works, metal works, carpentry/furniture. Besides, it has multidisciplinary teams made up of Electricians, HVAC technicians, bricklayers, welders, and woodworkers. They perform maintenance in all buildings of the university campus.

Summarized workflow for the maintenance of HVAC systems

The department for building maintenance has a structured flowchart, which presents responsibilities and tasks assigned to maintenance technicians to provide satisfactory attendance to HVAC maintenance. The customer requests maintenance using a web-based information technology (IT) system. The maintenance gatekeeper receives and analyses the request and then issues a work order (WO). Afterward, technicians receive the WO and visit the site for fault detection, diagnostics, and repair (FDD&R) air conditioning devices. The maintenance process in HVAC systems is summarized in Figure 2.

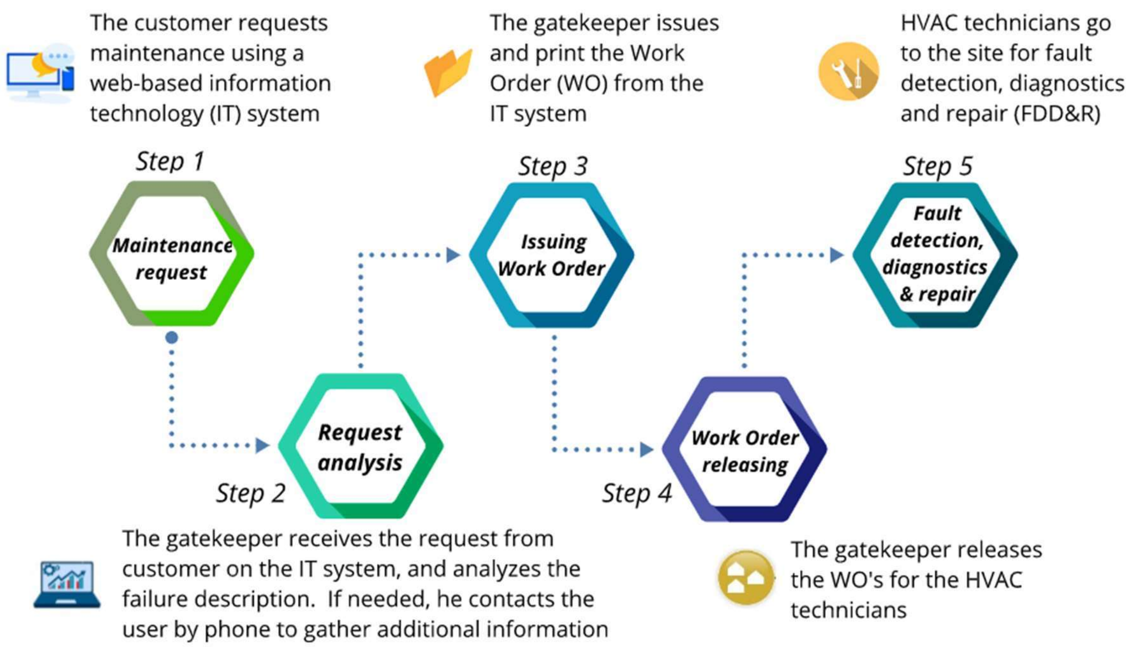

Figure 2: An overview of the maintenance workflow on the HVAC systems in buildings of the university campus

Participants

Four workers from the DBM had been consulted in the field research; three technicians specialized in the air conditioning and the maintenance gatekeeper. Technicians are responsible for installing, maintaining, and repairing air conditioning devices for all organization buildings. The maintenance gatekeeper plays the role of receiving and analysing requests, issuing work orders (WOs), and offering technical support. Informed consent was obtained from all subjects involved in the study.

Data collection

The data collection method is based on an ethnographic approach (Emerson et al., 2011). It consists of exploring how the frontline staff works, identifying tacit knowledge, dull routines, and issues in-situ (Furniss et al., 2019). This approach was used to gather information to build a representative FRAM model of the activities related to the maintenance of HVAC systems. Data collection instruments included:

(1) Observations of maintenance tasks, work order analysis, work planning, and interactions with customers
(2) Consulting the HVAC technicians and gatekeepers through conversation (de Carvalho et al., 2016). It comprises open questions, in which replays are recorded in field notes to be analysed later.
(3) Talking to customers informally as part of understanding the relationship with the maintenance

FRAM model

The FRAM model for working in the maintenance of HVAC systems consists of sixteen functions. They represent the WAD during the maintenance of HVAC systems. Hexagons concern functions, and lines concern couplings. The graphical representation of the integral FRAM model is presented in Figure 3. Functions depicted in green with a sine wave indicate functions showing variability. Each of these functions and their variability will be analysed with the cutting technique. FMV software (Hill, 2019) allows the graphical display of information and provides functional features to check the completeness of the functions.

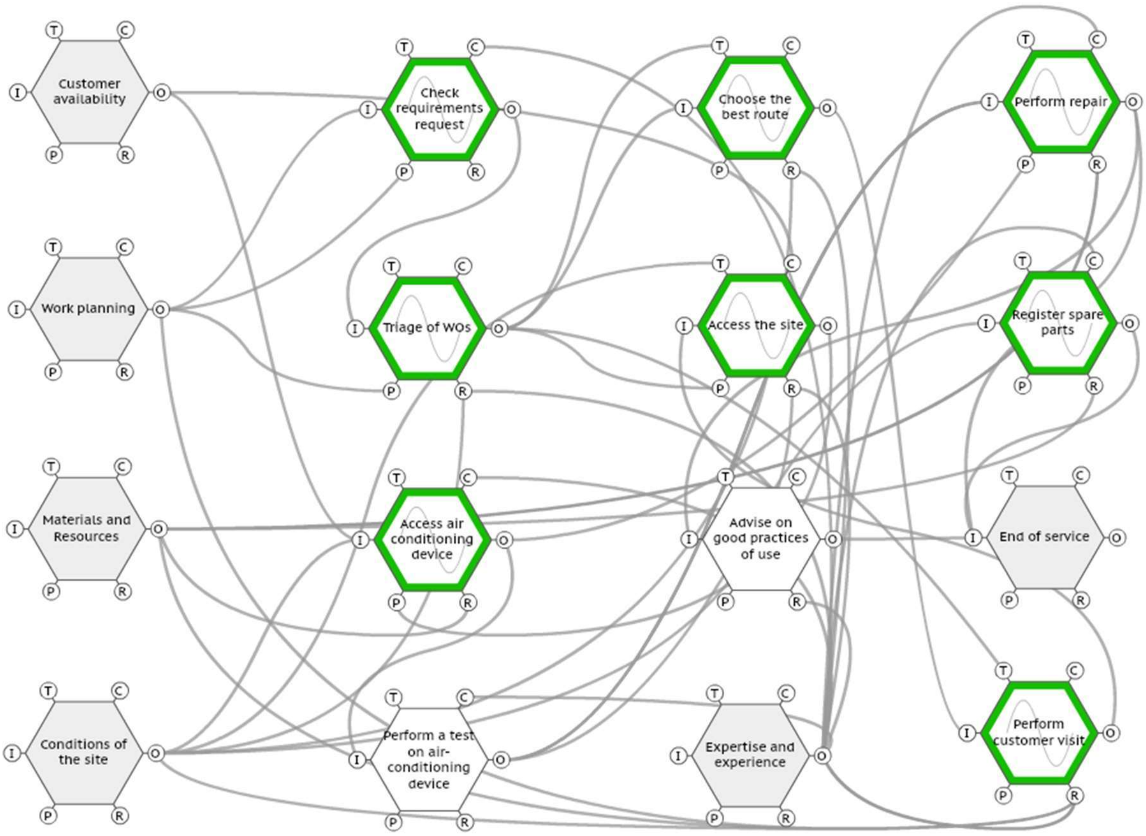

Figure 3: Integral FRAM model for the maintenance activity in HVAC systems

The model analysis starts from the function <check requirements request>, which consists of analysing the WOs to find the requirements for the maintenance. The function <work planning> represents the planning for daily work. This function requires several decisions collaboratively made in the maintenance team concerning strategies to be adopted during the work shift. HVAC technicians must verify the service requested, the service location, and any specific demands to visit the customer. Moreover, technicians take advantage of their expertise and experience to interpret data from WOs. As shown in Table 1, this function presents variability regarding time and precision. If the WOs are not issued somehow due to urgency or another factor, the activity may not occur. In the same way, if the information in the WOs is insufficient or ambiguous, there may be an error in the analysis.

The function <triage of WOs> represents the pivotal role played by HVAC technicians about WOs prioritization. As described in Table 1, the function <triage of WOs> is highly susceptible to variability in both timing and precision. Once WOs priority relies on the workers' tacit knowledge, which requires a long time to complete this task. This function is triggered every morning when the team meets to visit customers. This decision-making relies mainly on the workers' knowledge about the territory they operate. The knowledge of the territory is a crucial element in delineating an optimized route to avoid unnecessary pathways by the workers. Output quality depends on how thorough the failure description by the requestor is performed. Insufficient information entails increasing the possibility of inadequate prioritization of WOs, affecting the downstream function <choose the best route>.

Table 1: Summary of potential variability in the maintenance activities of HVAC systems

Function	Output	Variability regarding time		Variability regarding precision	
		Range	Description	Range	Description
Check request requirements	Requests checked	Not at all	If available information to work is insufficient, the output may not be performed at all.	Imprecise	The analysis may be an error due to the customer's description if the description failure is incorrect or incomplete.
Triage of WOs	Priority of WOs defined	Too late	This function is highly dependent on workers' expertise.	Imprecise	Output quality depends on how thorough the requestor's information is. Therefore, some WOs may be wrongly prioritized because of insufficient information from the requestor.
Choose the best route	Route	On-time	This function comprises the decision-making of the team. It is a function relatively quick.	Acceptable	Output precision depends on the workers' knowledge in the territory.
Perform customer visit	Access the site	Not at all	This function depends mainly on the weather conditions.	Imprecise	Non-issuance of WOs can lead to execution errors due to a lack of work information.
Access the site	Access air conditioning device	Not at all	If the customer is not in the local or unavailable, the output may not be produced.	Acceptable	Output precision depends on the workers' knowledge in the territory.
Access air conditioning device	Access air conditioning device to repair Perform test on the air conditioning	Not at all	If the conditions for performing the maintenance are adverse, the output may not be performed at all.	Imprecise	The quality of the access to air conditioning devices depends on the site's conditions (e.g., device installed on high outside position, confined space, or in the roof). These conditions may cause risky situations to workers or imply a non-perform of maintenance.
Perform repair	Repair performed	Not at all	It depends on spare parts availability. If there is no spare part to repair, the output may not be performed at all.	Imprecise	All the outputs depend on how thorough the tasks are performed.
Register spare parts	Parts registered	On-time	Mental effort consumes relatively little time related to the activity.	Imprecise	Unavailability of the form to record spare parts can lead to misunderstandings or errors.

Analysis with a layered FRAM from cutting technique

As aforementioned, this technique consists of cutting couplings in functions presenting variability and analyse them in secondary layers. For example, Figure 4 illustrates the eight couplings for the function <triage of WOs> as a layer from the integral FRAM model. This function represents a cognitive process that happens every morning after the team's meeting. It mainly uses variables as the work scope, which results from the function <check request requirements> and resources such as knowledge of the local and time of route as decision-making to prioritize the WOs. The potential variability of the function <check request requirements> relies on the possibility of the check not occur or occur with reduced precision. In these cases, the variability affects the function <triage of WOs>, as priorities might be wrongly set.

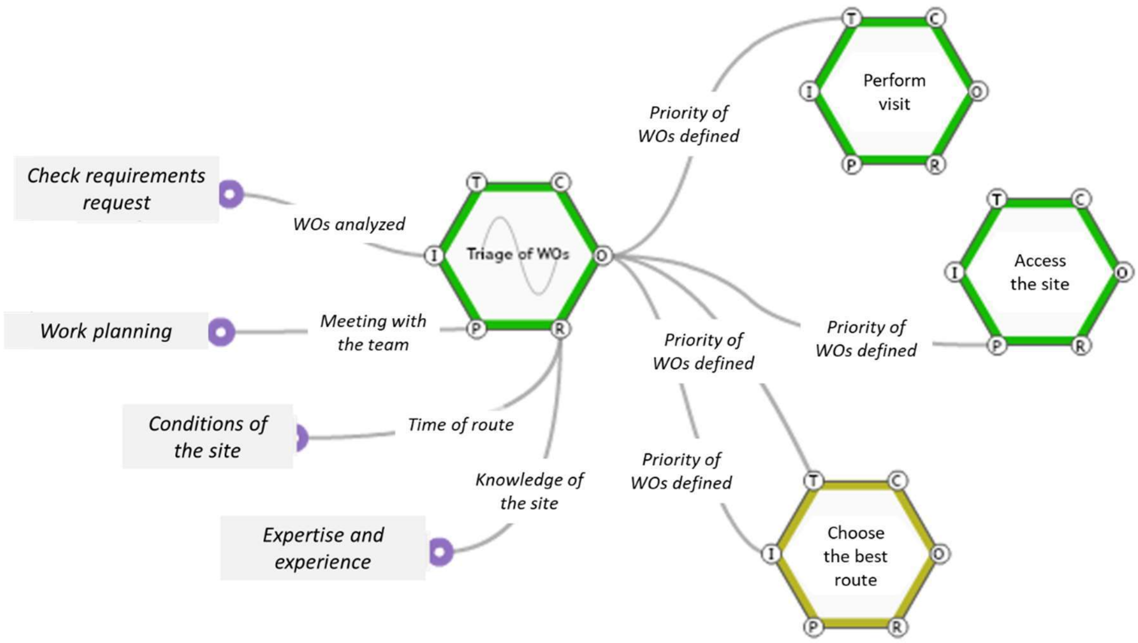

Figure 4: Layer from the integral FRAM model presenting how the function <triage of WOs> coupled with other functions

As detailed in Figure 5, the function <perform customer visit> takes advantage of the workers' expertise and experience, such as workers' knowledge on the territory and affinity with customers; this contributes to imitate an appointment. The weather conditions act as a decision element to the function, e.g., if there is a "heavy rain", the workers do not perform external services. On the other hand, the workers are exposed to rigorous solar radiation on hot days, causing a high physical workload and fatigue. To mitigate these effects, when possible, they do not perform activities that expose them to solar radiation in time between 11 am and 3 pm. This setting may lead to variability regarding the weather conditions faced by the time. Also, functions <work planning> and <materials and resources> technically support the visits with WOs and working tools. The output variability regarding precision occurred when the WOs were not issued on time; therefore, the workers need to perform a visit without the WOs at hand. In this scenario, it should be noted that some WOs are issued verbally on the site by technicians. The gatekeeper reported that flexibility is vital to allow quick response in unscheduled situations, i.e., this variability enables the attending faster in specific situations (e.g., lack of energy and water leakage) or to optimize the route of workers. On the other hand, this setting produces an imprecise output, leading to a high cognitive workload to the workers and potential execution errors.

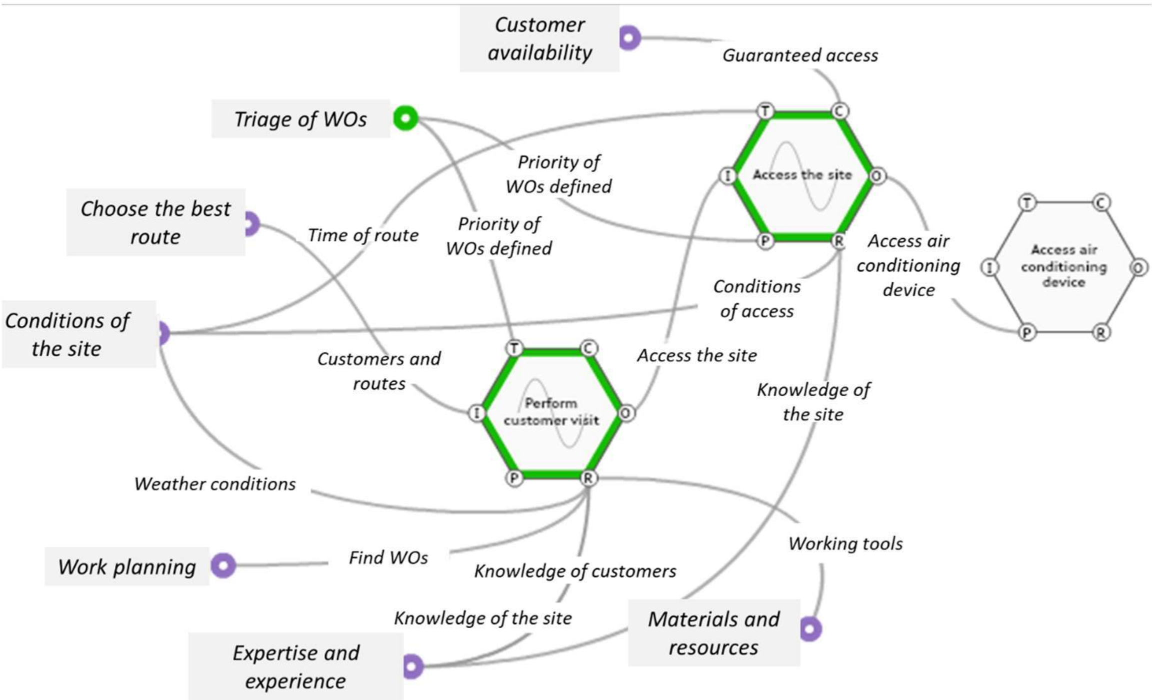

Figure 5: Layer from the integral FRAM model presenting how the functions <perform customer visit> and <access the site> coupled with other functions

Another fundamental function is <access the site>, which is the reason for many complaints by the workers. The function <customer availability> controls the decision-making about aborting or performing the repair. We noted in some cases that the team did not find anyone to receive them on arrival at the site. Faced with this situation, usually, they visit another customer or return to the workshop. This function uses resources like workers' expertise and specific conditions of the site to support the decision-making along with the activity.

Figure 6 presents the function <access air conditioning device> that works as a precondition to the <perform repair> downstream function. In addition, it consumes resources like access equipment (e.g., ladder or scaffolds) if the unit installations are on the roof or in high positions. Moreover, the absence of conservation in HVAC structures contributes to accidents involving the maintenance team. There are many territories with HVAC devices installed in places of difficult access or in confined spaces (i.e., devices installed on the roof or the underground), which significantly affect the workers' performance. Reports from workers reveal maintenance of units installed on the roof is the most exhausting type of work. This maintenance work is mainly due to the physical effort to carry the essential fixtures to the working (e.g., vacuum pump, a gas cylinder, and other working tools). Also, to perform this activity, workers are exposed to solar radiation, causing fatigue and a drop in blood pressure, representing a significant risk to workers' health. Our field observations found that it is pretty common for workers to access HVAC devices installed in such conditions.

According to the workers' reports, they receive scarce information in the WO about the site's conditions. The analysis revealed this configuration produces the most critical variability in the function <access air conditioning device> output, regarding both timing and precision, affecting the downstream functions and spreading along with the entire system. The background function <customer availability> is also a temporal constraint to trigger this function because if the customer is unavailable, workers cannot access the device to perform the repair.

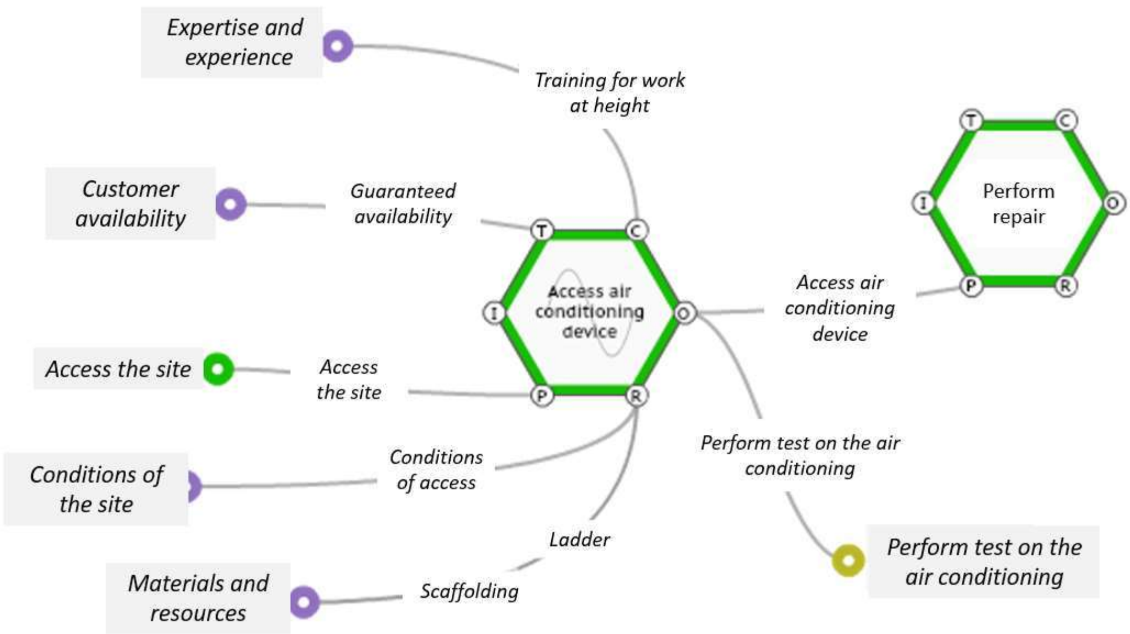

Figure 6: Layer from the integral FRAM model presenting how the function <access air conditioning device> coupled with other functions.

Field studies disclosed some disturbances regarding conditions of access to the air conditioning device. Moreover, these conditions increase the cognitive effort of HVAC technicians regarding their resilience abilities to cope with troubles. Table 2 describes the disturbances that were hampering access to the air conditioning device.

Table 2: Disturbances from conditions of access to the air conditioning device

Function	Conditions of access	Disturbance
Access air conditioning device	Overgrowth of vegetation	Some units are surrounded by vegetation hampering access to the device.
	Damaged structures	Some fixing structures are inferior (e.g., atrocious platforms), damaged by natural occurrences like rain.
	Confined spaces	Some units are installed in confined spaces that make access risky.
	Units on the roof	Depending on the height, they need special equipment (e.g., ladder or scaffolds) besides safety equipment to access these units.
	Roadblock	Hindrances in the pathway are hampering access.

Figure 7 shows the function <perform repair>. This function relies on the technicians' expertise and experience, mainly regarding their knowledge of the specific device. Moreover, this function consumes several resources, such as working tools, an oxyacetylene torch, and a vacuum pump. The resources needed to support the maintenance rely on the work scope. In some cases, workers need to return to the workshop to get additional tools to do the maintenance repair since the WOs do not provide the work scope properly. Furthermore, while workers perform the repair, they often deal with temporal pressures from the customer, increasing psychological distress.

As previously presented in Table 1, the potential variability regarding both timing and precision in the function <perform repair> depends on spare parts availability and working tools. If there is no spare part to perform the repair, the output may not be performed at all. Besides, workers adopt some strategies to cope with these constraints, as dismantling an old device to remove a part in condition of use.

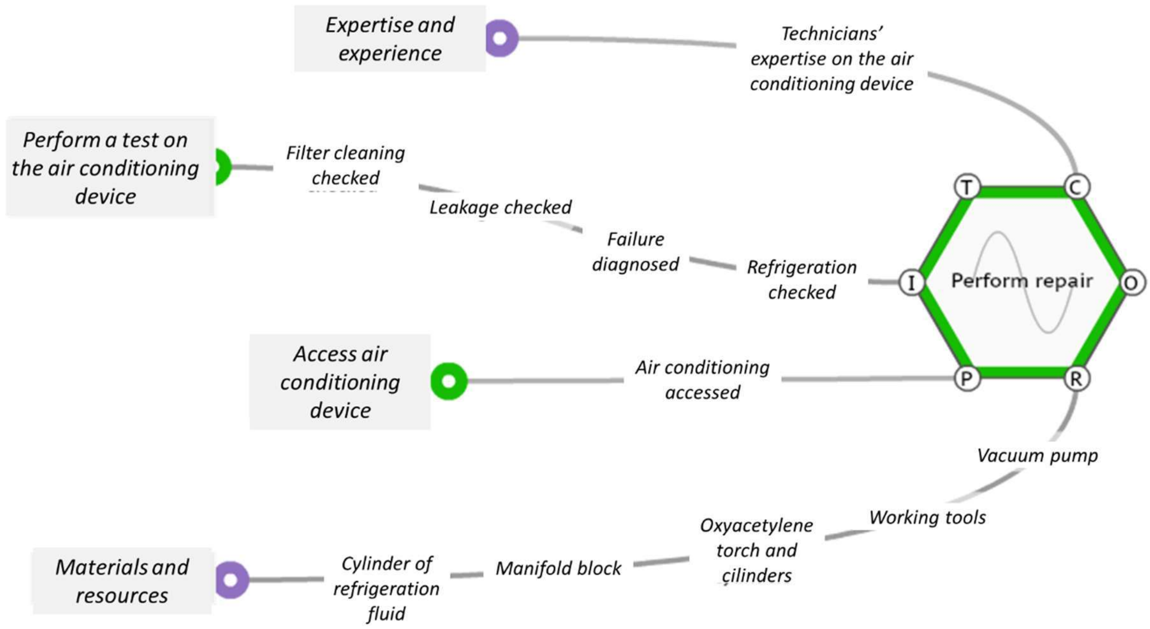

Figure 7: Layer from the integral FRAM model presenting how the function <perform repair> coupled with other functions.

According to Figure 8, four functions affect the performance of the function under analysis. The function <expertise and experience> controls the triggering of the <register spare parts> function once the technicians' knowledge is crucial to perform the task. Furthermore, this function consumes resources as a standard form used by the technician to record the spare parts. As previously shown in Table 1, whereas output variability regarding time is "on time", variability regarding precision is "imprecise". The imprecise output results from the unavailability of the standard form to record spare parts. To cope with this variability, workers appeal to the memory or an improvised handwrite sheet to record parts. As a result, this scenario increases the cognitive workload and can lead to misunderstandings or errors.

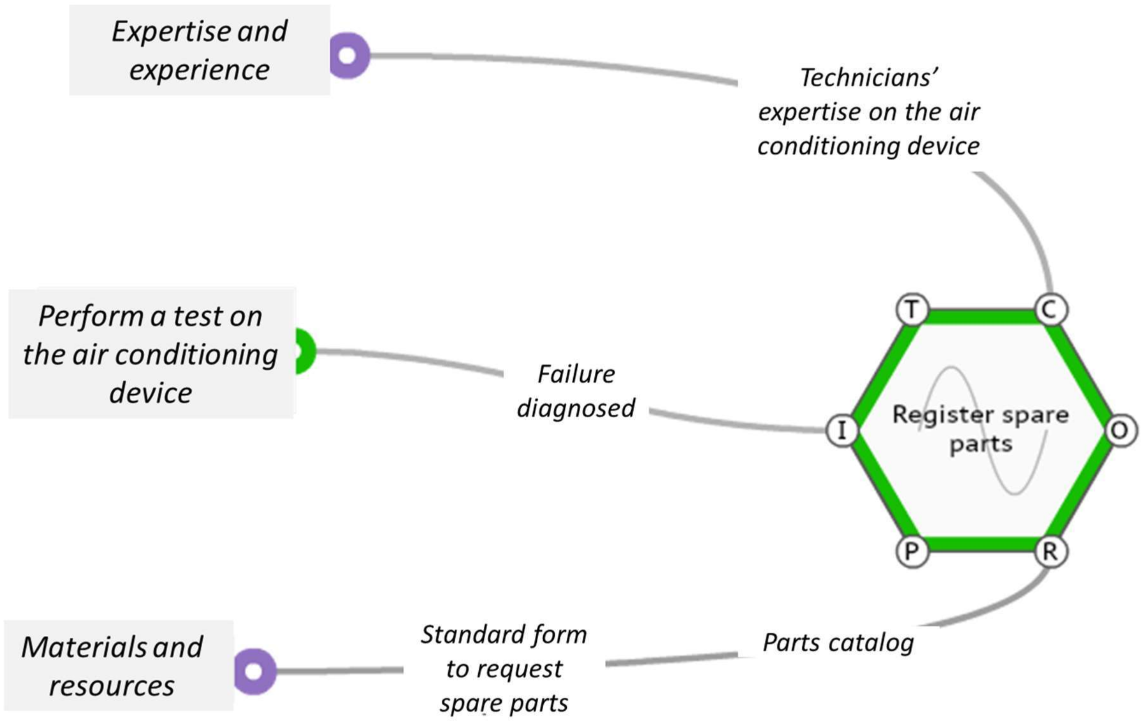

Figure 8: Layer from the integral FRAM model presenting how the function <register spare parts> coupled with other functions

Reflections on the WAD in the HVAC maintenance

Based on the results, several interesting points can be addressed. First, deviations must be considered in agreement with the concept of local rationality since, in some circumstances, they become unavoidable and even necessary to deal with the complexity of everyday work (Patriarca et al., 2018). Second, although the tasks and responsibilities somehow reflect an extract of work, the environment influences the functioning of HVAC technicians once their work relies on the conditions of the site and HVAC installations.

RE issues on HVAC maintenance are related to the execution abilities based on the unplanned maintenance approach, handling over 800 HVAC-related services annually. The absence of a preventive maintenance strategy increases the complexity of the work once workers need to deal with scarce resources, inadequate tools, and insufficient team to cover all the buildings on the university campus. Technicians walk throughout the campus (1-2 km) doing 4-hour operations with the working tools. There is a risk of occupational injuries due to the heavy load and physical demands of the activity. Often, HVAC technicians deal with downgraded sites, confined spaces, and hard-to-reach places, especially when the HVAC systems are installed in the roof or the underground. It is hard to predict or expect how the work of HVAC technicians will occur, given that work is done daily in different scenarios. Different work situations and urgency scenarios require various responses that prescribed guidelines and procedures are sometimes unable to predict. In this sense, the normal variability of the human being could be allied to cope with demands that complex socio-technical systems require daily.

Discussion

FRAM has been widely used to analyse complex socio-technical systems, proving to be a helpful tool for related purposes. FRAM is capable of presenting performance variability of the system rather than calculating some failure probability (Bjerga et al., 2016; Hollnagel, 2012), i.e., it aims to highlight how the system performance is affected by slight variations in functions and different contextual situations (Patriarca et al., 2020; Salehi et al., 2020).

FRAM's functional perspective enables identifying risks based on system functioning rather than identifying specific hazards stemming from a single function (Rosa et al., 2015; Yang et al., 2017). In addition, it is advocated in traditional methods for risk assessment, which can only provide negative experience about how the system fails rather than how they make success (Li et al., 2019). It is noteworthy that complex systems, even presenting inherent variability, do not fail most of the time. Besides, the same conditions and root causes often produce both failures and successful events (Das et al., 2018).

For example, analysis conducted in line with the RCA represents incidents as a chain of adverse events. Also, it considers human, technological, and organisational aspects as either causal factors or latent conditions (Alm and Woltjer, 2010). As opposed to linear cause-effect relationships, the perspective provided by the FRAM approach focuses more on the overall understanding of the functions, including their potential variabilities (Tian et al., 2016). Similar reflections can be noted when compared to FMEA. Sujan (2012) presents some difficulties related to the practical use of FMEA in healthcare to determine the consequences of failures since these are highly dependent on the contextual aspects.

While the FTA can explain how a failure (top event) is achieved from root causes (Toroody et al., 2016), the FRAM is deemed more efficient, useful, and advantageous by covering what may happen and representing dynamic interactions within the socio-technical system. In order to illustrate this fact, it can be noted that the function output variability in our case study can be stemmed from different sources, and this explains how the FRAM is beneficial to overcome shortcomings from reductionist tools, offering a holistic view of the system without losing deeper issues.

As stated previously, despite continuous efforts to enhance the FRAM model, further developments are needed to reduce insufficiencies or drawbacks of the method. For example, FRAM traditional approach presents an overwhelming complexity of graphical representation (Patriarca et al., 2018) since the hexagon-based representation is cluttered and its informative power is limited because it describes too many elements and respective relationships cannot be easily understood. Moreover, when organizing the results in text format, it becomes a long list of activities, exacerbated by many dependencies (Falegnami et al., 2019). Hence, FRAM's practical use is hampered by its intrinsic features, which discourages the diffusion and dissemination of the FRAM.

Starting from the relevant studies obtained applying FRAM for analysis of the WAD in complex socio-technical systems, this paper explores the possibility of enhancing FRAM's conventional formulation. Furthermore, this paper, employing the cutting technique, shows the benefit of the layered FRAM for clearly presenting how a function is influenced by other functions related to it.

Since the complexity of a socio-technical system is related to the intense interaction between agents, including the different nature of agents, dynamic behaviour, and uncertainty from the environment (Patriarca and Bergström, 2017), the representation of a layered FRAM become a helpful way for analysing the WAD without losing the systemic perspective. However, this study had not been focused on addressing the modelling for different agents and levels of abstraction, as presented in Patriarca et al. (2017a). Instead, the proposed approach aimed to understand how upstream functions influence a core function since the function's aspects are likely to be affected by the environment, making the function deviates from procedures and guidelines prescribed by designers (Duan et al., 2015).

The results show that it is possible to benefit by integrating the cutting technique into the FRAM model to promote the coupling analysis in secondary layers. This manner facilitates the judgment of elements that somehow affect downstream functions, leading to variability. Nevertheless, difficulties in establishing creative tactics to select the functions and subset of functions under consideration constitute a significant limitation in this investigation, which claims further studies in this topic.

Conclusions

FRAM application can provide interesting and useful results in analysing WAD in scenarios governed by the dynamic nature of complex socio-technical systems. However, as stated in the introduction, the graphical representation's complexity poses barriers to FRAM popularization. Therefore, this research intends to contribute with scientific discoveries concerning how to improve the FRAM's graphical appearance enabling a deeper and reliable understanding of complex systems. Thus, this question was answered by the novel way to analyse the FRAM results, i.e., using the representation in layers, which provides cleaning in the graphical presentation of the FRAM model, highlighting only the interest functions and their couplings.

The embedding of the cutting technique into the FRAM model provides the exploration of a new perspective to the method to popularize and spread it during the treatment of complex issues. Moreover, the study brings an opportunity to discuss how to clarify the couplings among functions, emphasizing how each upstream function affects a core function and consequently spreads variability all over the entire system. Hence, this technique has proved to be a fruitful and valuable tool to support analysts in modelling complex systems using FRAM, decreasing the analyst's cognitive effort and providing accuracy to the analysis. Finally, further research can consider the study in different model instantiations to provide a comparative assessment of the functions. Even a more extensive systemic analysis may help validate the proposed technique. Other methodological challenges for future research encompass the possibility to apply this technique into FRAM in different socio-technical systems, where a high complexity level requires relevant accuracy in the analysis of system models, including safety assessment methods. In addition, an enhancement in the computational architecture of software currently available for FRAM purposes could include cutting an interesting coupling to provide detailed representations if selected by the user.

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Appendix 2

Soft computing for nonlinear risk assessment of complex socio-technical systems

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Soft computing for nonlinear risk assessment of complex socio-technical systems

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A R T I C L E I N F O

Keywords:
Soft computing
Fuzzy sets
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Nonlinear method
Functional Resonance Analysis Method (FRAM)

A B S T R A C T

Work in socio-technical systems (STS) exhibits dynamic and complex behaviors, becoming difficult to model, evaluate and predict. This study develops an integrated soft computing approach for nonlinear risk assessment in STS: the functional resonance analysis method (FRAM) has been integrated with fuzzy sets. While FRAM is helpful to model performance variability in qualitative terms, the assessments are usually subjected to a high degree of uncertainty. This novel approach is meant to overcome the subjectivity associated with the qualitative analyses performed by experts' judgments required by FRAM. For demonstration purposes, the approach has been applied to model a waste recycling process for construction materials. The results show how the approach allows assessing and ranking critical activities in STS operations.

1. Introduction

Risk assessment is a crucial part of the occupational health and safety management system. It helps to identify potential hazards and to propose corrective and preventive measures (Alawad, Kaewunruen, & An, 2020; Huang & Zhang, 2021; Liu, Zhang et al., 2020; Obajemu, Mahfouf, & Catto, 2018; Yener & Can, 2021). There are several approaches in the literature driven to assess and rank critical elements within a process (e.g., fault tree analysis, event tree analysis, HAZOP, FMECA, etc.). However, these methods traditionally follow a constructivism-oriented perspective, based on the techno-centric bias which assumes it is always possible to identify a linear cause/effect relation (Patriarca, Falegnami, Costantino, & Bilotta, 2018). Since current technical systems have complex interactions with humans and organizations, traditional risk and safety approaches are no longer sufficient for assessing risks by considering only component failures (Kim & Yoon, 2021).

Acknowledging these limitations, new and robust methods, including an integrated view of technological, human, and organizational system components are needed to improve the analysis and modeling of highly complex systems (Patriarca et al., 2017a), which are characterized by being dynamic, incompletely described, and therefore underspecified (Hollnagel, 2012).

For reliable analysis and a better understanding of these systems, it might be applied a perspective in line with Resilience Engineering (RE), which concerns a new approach to the safety management that focuses on how systems anticipate undesirable conditions or manage changes, and thereby continue the operation, even after a disruptive event, or the presence of continuous stress (Hollnagel, Woods, & Leveson, 2006). One of the main methods in RE is the Functional Resonance Analysis Method (FRAM) (Patriarca et al., 2020), a well-established systemic method proposed by Hollnagel (2012). FRAM is superior to traditional tools since it does not identify only what can go wrong, nor the probability of failure of a single component or function, but it rather provides a deeper understanding of what may happen during a typical daily work activity, emphasizing the weakness of the complex system and suggesting proactive countermeasures (Patriarca et al., 2020).

1.1. Background

The FRAM has been widely applied for different purposes in several domains like aviation (Patriarca, Di Gravio, Cioponea, & Licu, 2019), construction (del Pardo-Ferreira, 2020; Rosa, Haddad, & de Carvalho, 2015), flood-risk (Anvarifar, Voorendt, Zevenbergen, & Thissen, 2017; Steen & Ferreira, 2020), healthcare (Jatobá et al., 2018; Kaya, Ovali, & Ozturk, 2019; Raben, Bogh, Viskum, Mikkelsen, & Hollnagel, 2017), maritime (Patriarca & Bergström, 2017; Vries & Bligård, 2019; Wahl,

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Abstract

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Keywords: soft computing; fuzzy sets; risk assessment; nonlinear method; Functional Resonance Analysis Method (FRAM)

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Despite its widespread use, the traditional FRAM is built using qualitative descriptions, including qualitative likelihood judgments on variability outcomes (Bjerga et al., 2016). In this sense, many authors have tried to evaluate the outcomes of FRAM models quantitatively or at least semi-quantitatively (Patriarca et al., 2020). To strengthen the method with decision-making features in risk assessment, the FRAM was integrated with Analytic Hierarchy Process (AHP) to assign weight factors for the identification of performance variability and the aggregation of variability (Alboghobeish & Shirali, 2021; França et al., 2019; Rosa et al., 2015). Other studies presented the Monte Carlo simulation as an option for quantifying the couplings among functions (Kaya et al., 2021; Kaya & Hocaoglu, 2020; Patriarca et al., 2017a; Patriarca et al., 2017b), among others. However, arguably the quantitative evaluation of FRAM involves parameters with a high degree of uncertainty due to the vagueness of human knowledge. For example, the variability in a single function and among functions in a FRAM model is basically hand-picked, this setting leads to low efficiency and poor thoroughness in the analysis (Duan et al., 2015). Likewise, as the quality of the output in FRAM directly depends on the experts' opinions and the information they provide as input for functions (Salehi et al., 2020), the evolutions of the FRAM in earlier studies have limitations to cope with such opinions. This is one of the reasons why it is more appropriate the application of fuzzy sets (Zadeh, 1965) to overcome the uncertainty introduced by the expert judgments, once the arbitrariness or uncertainty existing in the evaluating process of performance variability can be minimized through this approach (Hirose & Sawaragi, 2020; Slim & Nadeau, 2020).

It is widely recognized that soft computing techniques are relevant strategies to handle useful information from experts. Among these classic techniques, the fuzzy-base decision-making process has emerged as a backbone in several applications and developments nowadays. For example, some researchers are using fuzzy systems in multi-attribute decision-making (MADM) methods to reduce the influence of subjective preferences (J. Wang et al., 2021; W. Wang et al., 2022; Zhan et al., 2020, 2021), whereas others employ the same logic to solve multi-criteria decision-making (MCDM) problems (Cheraghi et al., 2021; Y. Liu et al., 2020; Zhang et al., 2021). The combination of fuzzy logic with artificial neural networks (ANN) (Raeihagh et al., 2020; Yariyan et al., 2020) to deal with the uncertainty of experts' opinions in decision-making has been investigated in risk assessment applications. Gul et al. (2018) carried out a novel approach for the risk matrix method based on the Pythagorean fuzzy analytic hierarchy process (PFAHP) and the fuzzy technique for order preference by similarity to the ideal solution (FTOPSIS) method to obtain a more accurate ranking of risk ratings in occupational health and safety.

In terms of studies of fuzzy theory in combination with FRAM analysis, it was seen that there are limited studies. For example, in a previous study by Bellini et al. (2017) a fuzzy logic-based method was established in an attempt to quantify the variability rate of functions in the FRAM model. Aligned with this study, the Q-FRAM extends and operationalizes the qualitative concepts of functional variability and dampening capacities. The Q-FRAM comprises a methodology aiming to create a single resilience index that expresses the total variability at an instant from the resilience cornerstones, i.e., anticipate, respond, monitor, and learn (Bellini et al., 2020).

On the other hand, Hirose et al. (2017) have integrated the fuzzy CREAM into the FRAM, in which common performance conditions (CPCs) have been applied to each function on the FRAM model. In Hirose and Sawaragi (2020) a multi-methodology involving a hierarchical fuzzy CREAM and cellular automaton was developed to grasp the visualized safety of socio-technical systems. Other relevant contributions are the application of fuzzy sets to evaluate both the internal and external variability manifested in each function on the FRAM model (Slim & Nadeau, 2019, 2020).

1.2 Research aim

The current study is different from the previous ones on several points: (1) Where this study evaluates the variability by using five linguistic terms, Slim and Nadeau (2019, 2020) consider only three terms. (2) The study of Slim and Nadeau (2019, 2020) does not include the indicator for dampening capacity in the fuzzy inference system (FIS). (3) While this study engages in computing the variability in the FRAM's couplings, Hirose et al. (2017) and Hirose and Sawaragi (2020) focus on evaluating CPCs belonging to each function. (4) Bellini et al. (2017) and Bellini et al. (2020) do not address the indicator for dampening capacity as the current study does.

Based on the motivations mentioned above, a hybrid methodology was proposed for the nonlinear risk assessment in STS. A demonstrative case study was given to illustrate the effectiveness and advantages of the proposed approach. To deal with the subjectivity associated with the qualitative analyses performed by experts' judgments required by FRAM, a FIS was adopted to quantify the variability and the dampening capacity in the FRAM model. The main contributions of this work can be summarized as follows:

1. A fuzzy-set-based approach has been proposed to deal with uncertainty from experts during the variability evaluation in FRAM models.

2. In order to generalize a methodology to solve practical problems, the evaluation of the dampening capacity was integrated into the variability to establish a new approach of risk assessment from the analysis of FRAM models.

3. A general cohesive index is developed to rank critical activities in STS operations.

This study brings a new viewpoint for risk assessment in complex STS based on real FRAM implementations. The significance of this study lies in the possibility of helping safety managers to decide on the most critical operational activities. The merit of the proposed FRAM-fuzzy not only lies in providing a way to deal with uncertainties from experts' opinions but also in reducing fuzzy rules explosion faced in operating a FIS by integrating the union-rule configuration (URC) to design fuzzy inference rules.

The rest of the paper is organized as follows: An overview of the research methodology is presented in Section 2. In Section 3, the proposed approach is applied in a case study concerning the risk assessment of the recycling process of construction waste. Section 4 provides the results and discussions. Finally, Section 5 presents the conclusions and future research directions.

2. Materials and methods

2.1. Functional Resonance Analysis Method (FRAM)

The FRAM (Hollnagel, 2012) is a systemic analysis method generally used for modeling complex STS. FRAM is well-suited to build a model of potential interactions among functions of a system and describe how variability may arise and propagate throughout this system (Rosa et al., 2015; Vries & Bligård, 2019).

Hollnagel (Hollnagel, 2012) defined four steps to implement the FRAM. First, identify and describe the functions required for a process. Each function is made up of six aspects graphically represented at the corners of a hexagon: Input (I) includes the function processes or transforms or that which starts the function; preconditions (P) must exist before a function can be performed; resources (R) are that which the function needs or consumes to produce an output; time (T) are temporal constraints affecting the function; control (C) establishes how the function is monitored or controlled and output (O) that is the result of the function.

In the second step, the functions' variability is characterized in terms of timing and precision. In time-related variability, an output can occur on time, too late, too early, and not at all. Not at all is used when the output may be not occurring. In terms of precision, the variability is classified as precise, acceptable, imprecise, and wrong.

The third step concerns the aggregation of variability. This step aims to analyze how the variability in the coupling of functions can propagate in the entire system. The analyses related to the variability characterization and the variability aggregation are performed by experts' judgments. This makes it entirely possible to introduce a fuzzy-based decision-support method, as described in Sect. 3.

The final step consists of managing and monitoring the performance variability. As variability must be seen as something useful and inevitable for system operation (Pardo-Ferreira et al., 2020), the most fruitful strategy is controlling the variability rather than constraining it (Wahl et al., 2020).

2.2. Mamdani Fuzzy Inference System

The Mamdani FIS comprises a formulating process and a mapping from a set of inputs to output by using fuzzy logic, which includes membership functions, logical operations, and if-then rules (Mamdani & Assilian, 1975). Such conditions can be found, for instance, in the case of FRAM models. A typical FIS procedure encompasses four stages (Geramian & Abraham, 2021): First, in the fuzzification stage, crisp inputs are converted into fuzzy numbers, and the Membership Functions (MFs), as well as the linguistic variables, are determined. A fuzzy number denoted by $\widetilde{N}$ is a fuzzy subset of real numbers (R), and its membership function (MF) is defined as$\mu_{\tilde{A}}(x): R \rightarrow [0,1]$, where $\mu_{\tilde{A}}(x)$ is the membership function for fuzzy set A. MFs have different shapes like trapezoidal, triangular, gaussian, etc. and the selection of the MFs type is commonly chosen arbitrarily based on the user experience, the belief of decision-makers, intuition, and contextual knowledge about the concept modeled (Zarei et al., 2021). Fuzzy sets with MFs of higher types contribute to the complexity of calculation and do not pose serious improvements in the accuracy of the calculation (Klir & Yuan, 1995). This study uses triangular fuzzy numbers (TrFNs) to implement the proposed approach for the sake of computational simplicity at the same time it offers a good compromise with accuracy. For instance, a TrFN denoted by $\widetilde{N}$*(l, m, u),* where *l*, *m,* and *u* were denoted as the smallest membership value, the most possible value, and the greater membership value, respectively. The membership grade $\mu_{\tilde{A}}(x)$ is defined as follows:

$$\mu_{\tilde{A}}(x) = \begin{cases} \dfrac{x-l}{m-l}, & if\ l \leq x \leq m; \\ \dfrac{u-x}{u-m}, & if\ m \leq x \leq u; \\ 0, & otherwise \end{cases} \tag{1}$$

Second, the construction of fuzzy rules is a core in the development of a FIS (Mendel, 2017). In rules-based inference systems, human knowledge is represented in the form of if-then rules as illustrated below.

$$If \begin{pmatrix} I_{1,1} = & \dots & AND & I_{2,1} = & \cdots & AND & I_{3,1} = & \dots \\ I_{1,2} = & \dots & AND & I_{2,2} = & \dots & AND & I_{3,2} = & \dots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ I_{1,n} = & \dots & AND & I_{2,n} & \cdots & AND & I_{3,n} = & \dots \end{pmatrix} Then\ Output\ is\ O_k$$

In this example $(I_1, I_2, and\ I_3)$ are inputs of the FIS. Also, *n* is the total number of combinations of inputs to produce an output, whereas *k* is the eligible linguistic label for the output in the *k*-th rule of the FIS. The number of rules in a FIS is usually an exponential function and relies on the number of inputs to the system and the number of linguistic labels that these inputs concern, which may deem the model unfeasible and difficult to realize. For example, a 3-input FIS with 5 linguistic labels per input represents a complete rule-base that covers all possible contingencies returning, therefore, 5^3 rules. It should be noted that a large number of rules do not seem reasonable and interpretable for human beings beyond the chance of mistakes in the inference process (Eghbal Ahmadi et al., 2020).

In this study, the rule-base for computing the relationship between inputs and output is defined by experts. However, to avoid the rules' explosion problem and for simplifying the computational effort, this study also uses fuzzy rules based on the union-rule configuration (URC) (Combs & Andrews, 1998; Weinschenk et al., 2003). This method for rule-based reduction is aimed at removing less significant or merging redundant rules.

Third, in the fuzzy inference and aggregation stage, the rules are evaluated through, for example, a Product or Minimum method. Afterward, the evaluation results for all rules are aggregated, e.g., via a Maximum or Sum method.

Finally, a defuzzification process is introduced at this stage. Among the many methods that have been proposed in the literature in recent years, this study used the centroid technique (Yager & Filev, 1993). The Centroid *(x^*)* was chosen because it is maybe the most popular and reflects reality quite accurately (Cox, 1994). It is given by the algebraic expression (Ross, 2010):

$$x^* = \frac{\int \mu_{\tilde{a}}(x).xdx}{\int \mu_{\tilde{a}}(x)dx} \quad (2)$$

2.2.1 Aggregating experts' opinions

Various methods employ a transformation function to unify the multi-granularity of opinions. This study uses the similarity method (Hsu & Chen, 1996) for aggregating the experts' opinions. The agreement degree (AD) between expert E_i and expert E_j is computed as in Eq. 3.

$$AD = \frac{\int_x \left(min\{\mu_{Ni}(x), \mu_{Nj}(x)\}\right)dx}{\int_x \left(max\{\mu_{Ni}(x), \mu_{Nj}(x)\}\right)dx} \quad (3)$$

Afterward, an agreement matrix (AM) of pair-wise agreement among experts is given by the matrix in Eq. (4). The diagonal elements of the matrix are all 1 because it is assumed that no expert influences itself.

$$AM = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ a_{21} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ a_{n1} & a_{n2} & \cdots & 1 \end{bmatrix} \quad (4)$$

The relative agreement of an expert (RA) E_i (i=1, 2, … *n*) is given by Eq. 5

$$RA_{E_i} = \left(\frac{1}{n-1} \sum_{j=1}^{n} \left(RA_{ij} \right)^2 \right)^{1/2} \qquad (5)$$

For each linguistic variable, a fuzzy number $\tilde{N}$ is obtained as in Eq. 6. Triangular fuzzy numbers $\tilde{n}_i$ are given in Table 1 as an example.

$$\widetilde{N} = \sum_{i=1}^{n} \left(\frac{RA_{E_i}}{RA_{E_i} + \cdots + RA_{E_n}} \right) . \tilde{n}_i \qquad (6)$$

2.3 The proposed FRAM-fuzzy approach

This section presents an overview of the proposed approach. This approach aims at verifying formulated assumptions over the demonstrative case study to deduce applications to FRAM in general to different contexts. Fig. 1 shows the flowchart of the methodology, which comprises a two-tiered framework with five steps. The details of these five steps are as follows.

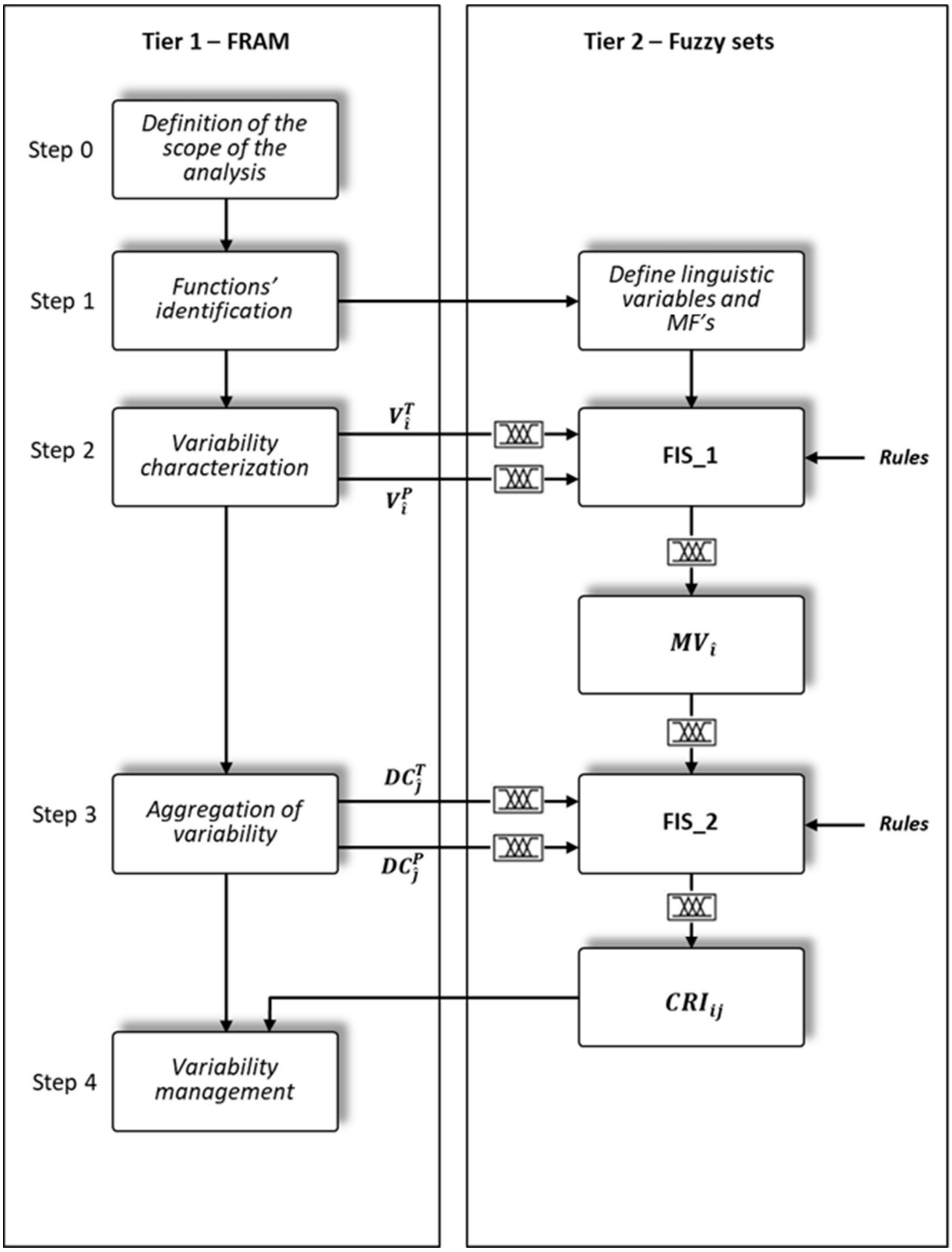

Figure 1 – Flowchart of the FRAM-fuzzy-based methodology

2.3.1. Step 0: Definition of the scope of the analysis

Following the theoretical concepts, the FRAM enables the analysis from a reactive approach such as an accident investigation or an examination with a proactive bias such as safety and risk assessment. The proposed methodology envisages FRAM to be used for risk assessment, and this paper investigates the possibility of combining the FRAM model and fuzzy sets theory to develop a friendly and useful framework for complex systems. To this extent, a pool of three FRAM experts cooperated to qualitatively evaluate the outputs of the FRAM model, and additionally for specifying the rule base for each

FIS. By FRAM experts, we mean analysts with experience with FRAM theoretical foundation and practical applications (preferably having applied FRAM before for other risk or accident analyses). Table 1 shows the general information about the experts involved in the assessment. It is worth mentioning that experts E1, E2, and E3 participated in the case study, whereas additional experts E4, E5, and E6 were invited to participate in the validation process after the case study explanation. The last ones were included to integrate the internal and external validation in order to provide different points of view, as well as complementary trustworthiness for the findings.

Table 1 - Expert general information

Expert	Experience in FRAM (years)	Background
E1	8	Civil Engineer, PhD, Researcher
E2	10	Electronics Engineer, PhD, Professor
E3	7	Electronics Engineer, PhD, Researcher
E4	5	Mechanical Engineer, PhD, Researcher
E5	7	Industrial Engineer, PhD, Professor
E6	2	Industrial Engineer, PhD Student, Work experience as Project manager

2.3.2. Step 1: Functions' identification, the definition of linguistic variables, and MFs

Tier 1 embraces the first step in the FRAM model, in which essential FRAM's functions are identified. Concurrently, tier 2 engages in defining linguistic variables and MFs to operate the FIS. In this paper, the indicators V_i^T (variability regarding timing) and V_i^P (variability regarding precision) are considered linguistic variables. V_i^T and V_i^P have four fuzzy sets with linguistic labels each one. The V_i^T includes the labels: not at all (NA), too late (TL), too early (TE), and on time (OT). Otherwise, V_i^P includes the labels: wrong (WR), imprecise (IM), acceptable (AC), and precise (PR). Concerning MFs, this study used TrFNs to implement the proposed approach for the sake of computational simplicity at the same time it offers a good compromise with accuracy. Tables 2 and 3 illustrate the linguistic labels and TrFNs designated for each linguistic label. The TrFNs used for evaluating the V_i^T and V_i^P are defined by the experience of authors, and the opinions of experts.

Table 2 - Linguistic labels and TrFNs for the variable timing, V_i^T

Linguistic label	**TrFN, $\tilde{n}_i$**
Not at all (NA)	[0 0 1]
Too late (TL)	[0 1 2]
Too early (TE)	[1 2 3]
On time (OT)	[2 3 3]

Table 3 - Linguistic labels and TrFNs for the variable precision, $V_{\hat{\imath}}^{P}$

Linguistic label	TrFN, $\tilde{n}_{\iota}$
Wrong (WR)	[0 0 1]
Imprecise (IM)	[0 1 2]
Acceptable (AC)	[1 2 3]
Precise (PR)	[2 3 3]

2.3.3. Step 2: Variability characterization

The second step consists of characterizing how each system's function varies with its potential and actual performance variability. According to the FRAM literature, a function may have multiple outputs; thus, it is possible to have a different variability for each output.

Evaluations obtained from experts' opinions were converted into TFNs by using Tables 2 and 3. Afterward, these opinions were aggregated by using Eqs. (3) – (6).

From a technical point of view, this study assumes an artificial indicator that represents the overall variability in the function output. As mathematically defined in Eq. 7, this indicator is called the magnitude of variability ($MV_{\hat{\imath}}$), for a generic function *i*. Using the FIS_1, a crisp value is obtained from aggregation between $V_{\hat{\imath}}^{T}$ and $V_{\hat{\imath}}^{P}$ (i.e., output variability regarding timing and precision, respectively).

$$MV_{\hat{\imath}} = V_{\hat{\imath}}^{T} \Lambda \, V_{\hat{\imath}}^{P} \qquad (7)$$

where,

$MV_{\hat{\imath}}$ represents the magnitude of output variability

$V_{\hat{\imath}}^{T}$ represents the variability of the upstream output *i* in terms of timing

$V_{\hat{\imath}}^{P}$ represents the variability of the upstream output *i* in terms of precision

Table 3 presents the linguistic labels for the output variable of FIS_1, which are VL, LO, ME, HI, and VH. These acronyms denote very low, low, medium, high, and very high, accordingly. For example, marking the label "Very Low" by the expert for a variable indicates the magnitude of variability of a function practically does not affect the functioning of downstream functions. Table 4 shows the TrFNs used for evaluating the MV, which were defined following the same logic as in step 1.

Table 4 - Linguistic labels and TrFNs towards output MV

Linguistic label	TrFN, $\tilde{n}_{\iota}$	Attribute
Very low (VL)	[1 1 3.25]	function's timing and precision have a negligible effect on how downstream functions are performed

Low (LO)	[1 3.25 5.5]	function's timing and precision have a limited effect on how downstream functions are performed
Medium (ME)	[3.25 5.5 7.75]	function's timing and precision have a potential effect on how downstream functions are performed
High (HI)	[5.5 7.75 10]	function's timing and precision have a serious effect on how downstream functions are performed
Very high (VH)	[7.75 10 10]	function's timing and precision have a huge effect on how downstream functions are performed

2.3.4. Step 3: Aggregation of variability

In this step, the aggregate variability is computed considering the dampening capacity of the functions since most of the variability can be dampened through internal adaptation in downstream functions (Bellini et al., 2020). The dampening capacity $DC_{\hat{j}}$ of a downstream function F_j is defined as the capability of F_j, in a certain context, of absorbing the $MV_{\hat{\imath}}$ and somehow providing acceptable outcomes (Bellini et al., 2017). In other words, the dampening capacity means that a system is able in minimizing undesirable effects resulting from uncontrolled variability. Therefore, this study suggests evaluating the $DC_{\hat{j}}$ in terms of timing and precision, i.e., DC_j^T and DC_j^P, as capabilities to damper variabilities. In this sense, as the dampening capacity of the variability is mostly related to how the downstream function deals with the upstream function's variability and the level of variability that the downstream function can handle (Kim & Yoon, 2021), becomes evident that the less a function has dampening capacity the chance of propagating variability for other functions grows. Table 5 summarizes the linguistic labels and TrFNs assigned to DC_j^T and DC_j^P following the same logic described in step 1.

Table 5 - Linguistic labels and TrFN for the input variables DC_j^T and DC_j^P

Linguistic label	TrFN, $\widetilde{n_\imath}$	Attributes
Very low (VL)	[1 1 3.25]	The function has a negligible capacity of dampening disturbances from upstream function
Low (LO)	[1 3.25 5.5]	The function has a limited capacity of dampening disturbances from upstream function
Medium (ME)	[3.25 5.5 7.75]	The function has an occasional capacity of dampening disturbances from upstream function
High (HI)	[5.5 7.75 10]	The function dampers most disturbances from upstream function
Very high (VH)	[7.75 10 10]	The function neutralizes all disturbances from the upstream function

Effects of the couplings among functions are difficult to be qualitatively understood (Yu et al., 2021) Therefore, the need to find a quantitative measure of couplings among functions is addressed in recent studies (Bellini et al., 2020; Kaya et al., 2019, 2021; Kaya & Hocaoglu, 2020). In this study, the Coupling Response Index (CRI_{ij}) is proposed as a novel indicator driven to examine how system performance affects and is affected by the coupling variability, the results are used for variability management. CRI_{ij} expresses the response in pair-wise coupling and translates the effect of variability in the upstream i-th function, dampened or amplified by the downstream j-th function. The results of the analysis can support identifying the potential threats and opportunities that need more attention in each coupling. Fig. 2 sketches the relationship between $MV_{\hat{\imath}}$ and $DC_{\hat{\jmath}}$, in which generates a response in a specific coupling.

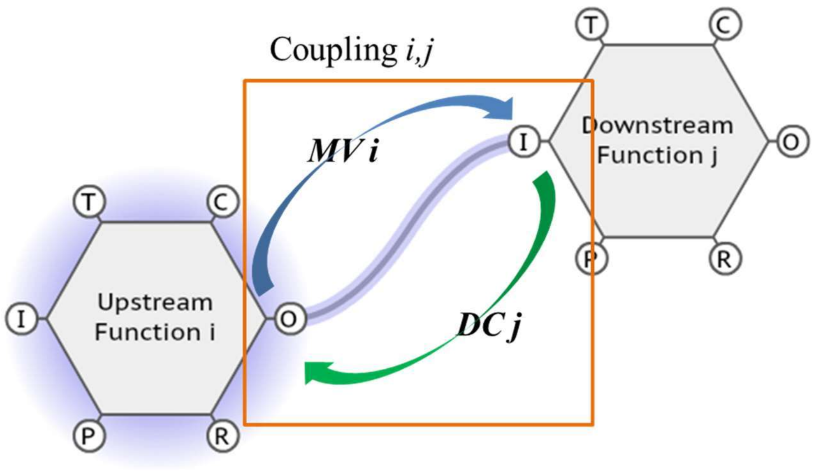

Figure 2 – Example of coupling response index (CRI) between an upstream i-th and the downstream j-th function

The coupling response parameters cannot be successfully evaluated in a linear relationship. Hence, a fuzzy belief rule-based system is constructed to obtain an index representing the behavior in the couplings. CRI_{ij} is defined as a 3-tuple $CRI_{ij}\left(MV_{\hat{\imath}}, DC_{\hat{\jmath}}^{P}, DC_{\hat{\jmath}}^{T}\right)$, which is obtained by operating the FIS_2, as indicated in Eq. 8. The same MFs used to operate the FIS_1 have been used for data computation in the FIS_2.

$$CRI_{ij} = MV_{\hat{\imath}} \Lambda\, DC_{\hat{\jmath}}^{P} \Lambda\, DC_{\hat{\jmath}}^{T} \qquad (8)$$

Where:

CRI_{ij} represents the coupling response index

$DC_{\hat{\jmath}}^{T}$ represents the dampening capacity of a downstream j-th function in terms of timing

$DC_{\hat{\jmath}}^{P}$ represents the dampening capacity of a downstream j-th function in terms of precision

The obtained result for CRI_{ij} is thus a metric ranging between 0 and 5, and the output system have at least five fuzzy sets to aggregate the $MV_{\hat{\imath}}, DC_{\hat{\jmath}}^{T}$ and $DC_{\hat{\jmath}}^{P}$ more precisely. Greater response in couplings indicates higher chances for functional resonance in the system. A set of linguistic labels are defined for the output variable of FIS_2, as indicated in Table 6, as well as the TrFNs which are defined following the same logic as in step 1.

Table 6 – Linguistic labels and TrFN for the output variable CRI_{ij}

Linguistic label	TrFN, $\tilde{n}_{\iota}$
High dampening (HD)	[0 0 1]
Low dampening (LD)	[0 1 2]
No-effect (NE)	[1 2 3]
slight amplifying (SA)	[2 3 4]
high amplifying (HA)	[3 4 5]

2.3.5. Step 4: Variability management

Ultimately, the provision of numerical values as the response index for each coupling in the system enabled the evaluation of critical functions for managing variability. Since a FRAM model is equivalent to a simple directed graph (or digraph), in this step a matrix $\boldsymbol{A_n}$ was built to represent the amount of CRI_{ij} for each upstream function, where a_{ij} is the value of the *k*-th CRI between F_i and F_j as listed in the row of Eq. (9), and the *n* is the number of functions.

$$\boldsymbol{A_n} = \begin{array}{c} \\ F_1 \\ F_2 \\ F_3 \\ \vdots \\ F_i \end{array} \begin{array}{c} \begin{array}{ccccc} CRI_{ij} & \cdots & \cdots & \cdots & CRI_{ij} \end{array} \\ \begin{bmatrix} a_{11} & a_{12} & a_{13} & \cdots & a_{1k} \\ a_{21} & a_{22} & a_{23} & \cdots & a_{2k} \\ a_{31} & a_{32} & a_{33} & \cdots & a_{3k} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & a_{n3} & \cdots & a_{nk} \end{bmatrix} \end{array} \tag{9}$$

where $\forall a_{ij},\ a_{ij} = \begin{cases} CRI_{ij}, & if\ exists\ a\ coupling\ from\ F_i\ to\ F_j \\ 0, & otherwise \end{cases}$

$$\Leftrightarrow \boldsymbol{A_n} = CRI_i = \sum_{i \neq j}^{k} a_{ij} \tag{10}$$

Eq. (10) suggests that the cumulative CRI_i for each upstream function F_i can be obtained by the sum of all elements a_{ij} in the row where the coupling represents a digraph from F_i

to F_j. For example, in this FRAM application, the function F4 (leveling control) is linked to downstream functions F5 and F6, i.e., the cumulative CRI_4 comprises the summation of CRI_{45} and CRI_{46}.

3. Demonstrative case study

This section presents a real case implementation to prove the good performance of the proposed method, as illustrated in Fig. 1. For this purpose, the recycling process of construction waste during the modernization work on the Maracanã stadium in Rio de Janeiro was selected.

This study used the software FMV (Hill, 2019) – FRAM Model visualizer – to build the graphical representation of the functions and their couplings. For the inference, it was used the MATLAB® Fuzzy Logic Toolbox since it provides user-friendly graphical interfaces and reliable environments for structuring and computing fuzzy systems. The details of the implementation are presented onwards.

3.1. Step 0: Definition of the scope of the analysis

The scope of the analysis in the proposed FRAM-fuzzy is to provide a predictive method for risk assessment in complex STS.

3.2. Step 1: Functions' identification

Fig. 3 shows the macro-process of the target system for this demonstrative case study. The recycling process includes four phases. First, the demolished concrete is selected preferably in the places of origin of the waste, immediately after generation. The waste sorted is delivered to the crusher using loaders. Afterward, the material is processed by using the mobile jaw crusher equipped with a magnetic extractor, which allows the removal of all magnetic material prior to the passage of the crushed material by the conveyor belt. Finally, the crushed material is delivered through the conveyor belt into the back of a truck.

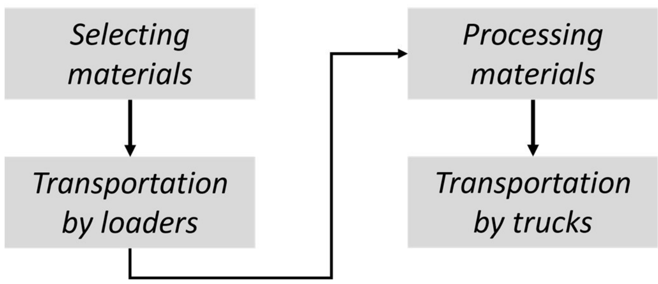

Figure 3 – Macro-process of recycling of construction waste

The processes in Fig. 3 served as basis to capture relevant functions to build the FRAM model. Therefore, a total of eight functions were defined in the recycling process of construction waste, as shown in Table 6. In addition, their potential coupling was defined as shown in Fig. 4. The links among functions define how these functions are coupled together within the system. The functions have been depicted here based on previous work from Rosa et al. (2015). Function numbers from F1 to F8 were used. It should be noted that function names in Table 7 and Fig. 4 are different from those in Fig. 3 since the latter were unfolded in specific functions by the convenience of the FRAM analysis.

Table 7 – Functions' description with six aspects

Function	Input	Output	Precondition	Resource	Control	Time
F1 Material selection	-	Material is selected	-	-	-	-
F2 Receive material	Material is selected	Material is received	Operation without load is completed	-	-	-
F3 Control of the finished product	Crushing process is completed	Control of product is executed	-	-	-	-
F4 Leveling control	-	Leveling control is completed	The initial checklist is completed	-	-	-
F5 Operation under load	Material is received	Control with load Crushing process is completed	-	-	Control of product	-
F6 Operation without load	-	Operation without load is completed	The initial checklist is completed	-	Control performed	-
F7 Material delivery	Control of product is executed	-	-	-	-	-
F8 Initial checklist	-	The initial checklist is completed	-	-	-	-

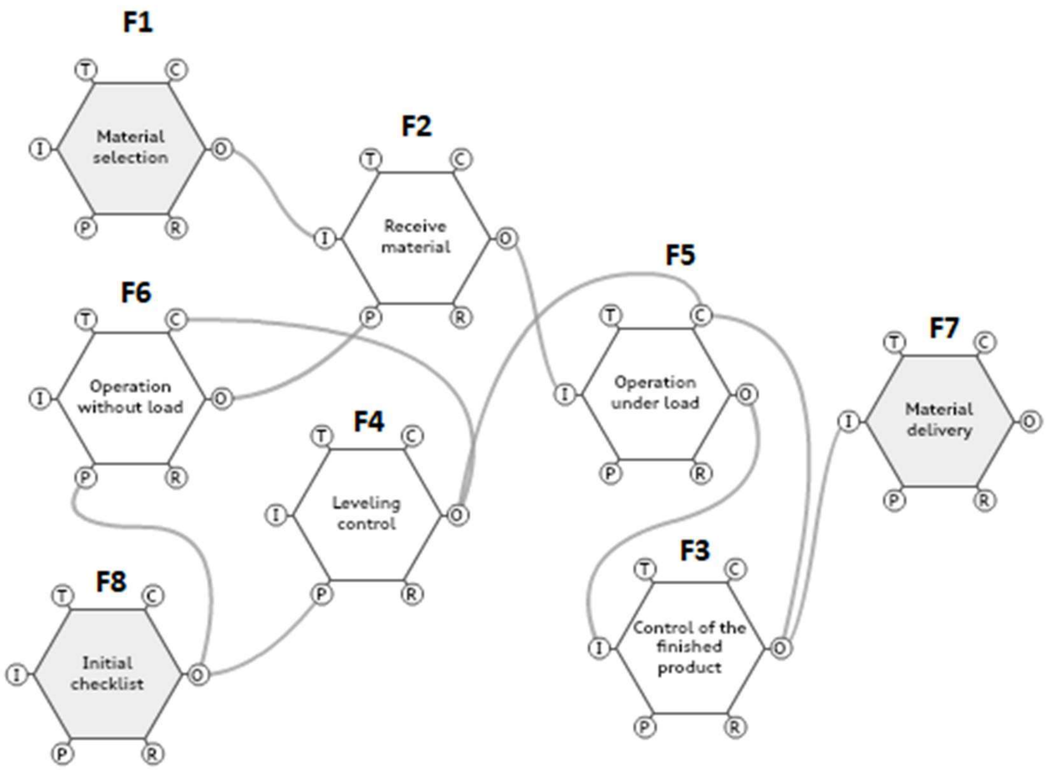

Figure 4 – Instantiation of the model for the recycling process of construction waste

Source: Rosa et al. (2015)

3.3. Step 2: Variability characterization

Functions presenting variability in the FRAM have been characterized individually, describing all the necessary aspects and phenotypes of potential variability, which has been qualitatively evaluated by the experts involved in the study, following Hollnagel's simple solution (Hollnagel, 2012), i.e., in terms of timing and precision. In time-related variability, an output can occur on time, too late, too early, and not at all. Otherwise, the precision is evaluated as precise, acceptable, imprecise, and wrong, represented here by their respective acronyms. Table 8 shows the FRAM's qualitative evaluation regarding the variability indicators V_i^T and V_i^P. Note that F7 is not evaluated regarding output variability once it does not produce output.

Table 8 – FRAM's qualitative evaluation regarding timing and precision

Expert \ Function		F1	F2	F3	F4	F5	F6	F7	F8
E_1	V_i^T	TL	OT	TL	OT	NA	OT	-	OT
E_2		TL	TE	TL	OT	TL	OT	-	TE
E_3		TL	OT	TE	OT	NA	OT	-	OT
E_1	V_i^P	IM	AC	IM	PR	WR	AC	-	PR
E_2		WR	IM	IM	PR	WR	IM	-	PR
E_3		AC	AC	WR	AC	IM	AC	-	AC

Next, to operationalize the FIS_1 a set of rules was determined based on the experience of the pool of experts in previous implementations of FRAM, following the logic of the URC technique. Its worthy notice that the rule base was tailored to operationalize the demonstrative case study. Thus, a set of thirteen fuzzy rules was defined for operating the FIS_1, as illustrated in Table 9. Note that rule 13 is a special rule, once if a NA linguistic label occurs at the V_i^T, the output result will be automatically VH, regardless of the input at the precision V_i^P.

Table 9 – Rule base for MV indicator

Rule	IF Timing is	and Precision is	then MV is
Rule 1	OT	PR	VL
Rule 2	OT	AC	LO
Rule 3	OT	IM	ME
Rule 4	OT	WR	HI
Rule 5	TE	PR	LO
Rule 6	TE	AC	ME
Rule 7	TE	IM	HI
Rule 8	TE	WR	VH
Rule 9	TL	PR	LO
Rule 10	TL	AC	ME
Rule 11	TL	IM	HI
Rule 12	TL	WR	VH
Rule 13	NA	none	VH

The qualitative evaluations were aggregated using Eqs. (3) – (6). The calculations for functions F1 to F8 of the FRAM model were done in the same way as the one made for function F3 <control of the finished product> as exemplified in Table 10. The fuzzy number of combined expert opinions regarding timing for function F3 was $\tilde{N}$= (0.264; 1.264; 2.264), as calculated using Eq. 5.

Table 10 – Values of relative agreement (RA), experts' opinions, TrFN, and normalized agreement of the experts regarding timing on function F3

Expert	**Linguistic label**	**TrFN, $\tilde{n}_i$**	RA_{E_i}	**Normalized, $RA_{E_i}/\sum RA_{E_i}$**
1	TL	[0 1 2]	1.005	0.368
2	TL	[0 1 2]	1.005	0.368
3	TE	[1 2 3]	0.721	0.264
$\sum =$	-	-	2.731	1

Following that, the FIS_1 was fed to calculate MV_i values for each function from F1 to F8. Table 10 summarizes the MV_i values obtained in the chosen scenario. The MV_i values were ranged between 3.26 and 8.41. As can be seen in Table 11, F5 has the most significant output variability. The reason is that both input variables – V_i^T and V_i^P – were evaluated by the experts with extreme potentials of variability, i.e., as can be seen earlier, two of them assigned NA and WR – "not at all" and "wrong" – to $V_{\hat{\imath}}^{T}$ and $V_{\hat{\imath}}^{P}$, respectively. In the FRAM semantic, "not at all" represents the possibility that output either is not produced at all or is produced so late that becomes useless for its purposes Similarly, a "wrong" output means the downstream function requires improvisation to cope with this, amplifying the function variability (Patriarca et al., 2017a).

Conversely, the returned value of magnitude from F4 is the smallest among all the functions. It makes sense once the experts unanimously indicated that output from F4 is produced "on time", which under typical conditions may dampen the variability. Also, in terms of precision, most of the experts assigned the same output as "precise" or least "acceptable". It means this condition favors the good progress of the system.

Table 11 – Results for the magnitude of variability (MV_i)

Function		Input, $\tilde{N}$		Output
		Timing, $V_{\hat{\imath}}^{T}$	Precision, $V_{\hat{\imath}}^{P}$	MV_i
F1	Material selection	1	0.996	7.75
F2	Receive material	2.733	1.736	4.78
F3	Control of the finished product	1.264	0.732	7.84
F4	Leveling control	3	1.998	3.26
F5	Operation under load	0.267	0.267	8.41
F6	Operation without load	3	1.736	3.93
F7	Material delivery	-	-	-
F8	Initial checklist	2.733	1.998	3.94

3.4. Step 3: Aggregation of variability

Once estimated the values of MV_i for each function, the experts also evaluate the dampening indicators $DC_{\hat{\jmath}}^{T}$ and $DC_{\hat{\jmath}}^{P}$ of each of 10 couplings, as shown in Table 12.

Table 12 – SMEs qualitative evaluation for each coupling F_{ij}

Expert \ Coupling		F_{12}	F_{25}	F_{53}	F_{45}	F_{35}	F_{37}	F_{46}	F_{62}	F_{84}	F_{86}
E_1	$DC_{\hat{\jmath}}^{T}$	HI	LO	ME	VH	VH	VL	VH	HI	ME	HI
E_2		ME	LO	HI	HI	HI	LO	HI	HI	ME	VH
E_3		VH	VL	ME	ME	VH	VL	HI	VH	HI	VH
E_1	$DC_{\hat{\jmath}}^{P}$	LO	VL	LO	LO	ME	ME	ME	ME	LO	ME
E_2		ME	VL	VL	LO	HI	ME	HI	HI	LO	HI
E_3		LO	LO	LO	ME	VH	LO	ME	HI	ME	HI

The rules of the FIS_2 were determined following the same logic as in step 1, and these rules are shown in Table 13. Following this logic, it seems meaningful to define a rule, e.g., if the MV_i is Very Low, in this scenario the CRI_{ij} is categorized as High Dampening, regardless of the singly outcomes for dampening factors.

Table 13 – Rule base for CRI indicator

Rule	MV_i	DC_j^T	DC_j^P	CRI_{ij}
Rule 1	VL	none	none	HD
Rule 2	none	VL	none	HD
Rule 3	none	none	VL	HD
Rule 4	LO	none	none	LD
Rule 5	none	LO	none	LD
Rule 6	none	none	LO	LD
Rule 7	ME	none	none	NE
Rule 8	none	ME	none	NE
Rule 9	none	none	ME	NE
Rule 10	HI	none	none	SA
Rule 11	none	HI	none	SA
Rule 12	none	none	HI	SA
Rule 13	VH	none	none	HA
Rule 14	none	VH	none	HA
Rule 15	none	none	VH	HA

Afterward, the FIS_2 was fed to calculate the CRI_{ij} for each coupling, as shown in Table 14. Amongst 10 couplings, 5 (i.e., F_{45}, F_{46}, F_{62}, F_{84}, and F_{86}) presented values less than 2. This means that these couplings may be classed as low dampening (LD). On the other hand, the couplings F_{12}, F_{25}, F_{53}, and F_{35} returned CRI values between 2 and 3. Thus, these couplings may be considered as no-effect (NE) in downstream functions. As can be seen in Table 14, the coupling F_{37} is those presenting the highest CRI value, and consequently, prone to propagate variability in the system. This is due to the small time-dampening capacity from F7 in facing the significant magnitude from F3 (MV_3 = 7.84).

Moreover, an important property to be considered in complex systems is resilience. In other words, a resilient system should be able to adjust its functioning to respond to disturbances. Thus, referring to Table 14, it should be noted that increasing either the DC_j^T or DC_j^P of downstream functions, the CRI in this coupling reduces its potential. This means the coupling is considered less prone to propagate variability throughout the system. An example of this is given in the couplings F_{84} and F_{86}.

Table 14 - Result for the CRI_{ij} for each coupling F_{ij}

Coupling	Input			Output
	MV_i	DC_j^T	DC_j^P	CRI_{ij}
F_{12}	7.75	4.821	3.931	2.53

F_{25}	4.78	2.650	1.600	2.72
F_{53}	8.41	6.181	2.650	2.50
F_{45}	3.26	7.757	3.931	1.95
F_{35}	7.84	9.399	9.243	2.04
F_{37}	7.84	1.600	4.819	3.01
F_{46}	3.26	8.417	6.965	1.30
F_{62}	3.93	8.350	7.069	1.29
F_{84}	3.94	6.181	4.035	1.99
F_{86}	3.94	9.40	7.750	1.14

3.5. Step 4: Variability management

Ultimately, the proposed approach aimed to develop tools for risk assessment through managing variability, acknowledging that the variability of functions might not always help accomplish the goals of the system; conversely, it might likely aggregate, which might lead to uncontrolled performance variability (Kaya & Hocaoglu, 2020). How to use couplings' responses to assess the criticality of functions in complex STS is a crucial task. Thus, the calculation of the cumulative CRI_i in each function could be derived using Eq. (10). Numerical values enabled the identification of critical functions. A higher number indicates a higher priority in risk assessment. Table 15 shows the results of the cumulative CRI_i for all functions listed in this case study. Note that F7 was not evaluated since it does not produce output.

The top three rankings for critical functions were F3, F4, and F8 while F5 and F6 are the functions with the lowest risk priority. F3 <control of the finished product> is the most critical function that should be monitored and controlled in the recycling of construction waste. Although F3 has not the highest MV, it still affects the priority of the function criticality. Thus, the obtained result illustrates that F3 requires enough attention by managers since the coupling F_{37} represents the highest noted CRI in the analysis. Note that the final ranking orders can be certainly influenced by dampening levels $DC_j^{T,P}$ in downstream functions. For example, comparing the results of Table 14 shows that F7 <material delivery> has a reduced capacity for controlling the variability from F3, mainly in dampening the variability in terms of timing (DC_7^T). Furthermore, decision-makers could implement measures to enhance the resilience of F7, whereas allocating suitable resources for improving the performance of F3.

The output variability value of the F4 <leveling control> (MV_4 = 3.26) means that it has a limited effect on how downstream functions are performed. However, F5 <operation

under load> presents a limited capacity to damper disturbances from F4, mainly in terms of precision. On the other hand, F4 has been coupled with F6 <operation without load> which presents substantial dampening capacity both in terms of timing and precision. Similarly, by considering the single results of F_{84} and F_{86} obviously, these couplings were ranked fifth and tenth CRI value, as shown in Table 14. Nevertheless, it is claimed that the propagation and aggregation of the performance variability due to dependencies among functions may result in undesirable outcomes (Anvarifar et al., 2017). Therefore, the cumulative CRI ranks F8 in the third priority level. The cumulative CRI for each function is advocated in this paper in considering even "weak signals" of failures. Thus, as the variability spreads the range of unwanted outcomes to be discovered from the couplings among functions gradually wide, and the variability effect becomes amplifying.

Table 15 – Ranking of critical functions

Function		CRI_i	Ranking
F1	Material selection	2.53	5
F2	Receive material	2.72	4
F3	Control of the finished product	5.05	1
F4	Leveling control	3.25	2
F5	Operation under load	2.50	6
F6	Operation without load	1.29	7
F7	Material delivery	-	-
F8	Initial checklist	3.13	3

3.6. Validation

To validate the results of previous stages, a focus group was established afterward. The discussion was held with the three experts who had been involved in the original study, and also three additional FRAM scholars not being exposed to the original case study construction. The general information about the experts was previously shown in Table 1.

The focus group was conducted through video conferencing for all participants, in five phases. Initially, an explanation of the new method was conducted in a workshop (about 1 hour). For the experts involved in the case study, this step preceded the actual usage of the method, conducted individually (about 3 hours). For the experts involved in the subsequent validation, this step was substituted with a demonstrative workshop (about 1 hour) to show the results of the use case and the methodological application. Subsequently, two debriefing workshops were conducted with the two groups of experts.

At this stage, participants were asked to answer a set of questions in order to evaluate different aspects of the method. Adjustments to the method were discussed based on the feedback being received, and lastly a final revision in a second workshop for further validation to check whether the experts perceived any remaining major criticality (1 hour per each group of respondents).

The set of questions we used to validate the method can be grouped into 3 categories:

1. *Effectiveness:* this category intends to verify whether the method can provide reliable results. This point is validated by two questions: *"Q1.1. Considering your own experience with FRAM, to which extent does the method provide useful results?"*, and *"Q1.2. To which extent may the quantitative result complement the qualitative evaluation?"*
2. *Relevance:* this category intends to verify whether the results provided by the new method may extend traditional approaches when assessing risks. For this purpose, we ask one more question: *"Q2. How do you compare the findings of this method with the ones achievable using traditional techniques (e.g., FMECA, FTA, ETA, HazOp)?"*
3. *Feasibility:* this category aims to validate whether the method may represent a viable solution for practical applications. *"Q3.1. To which extent do you believe this method can be replicated ensuring internal/external validity?"*, and *"Q3.2. How do you rate the benefit/cost relationship when using the method?"*. The first question serves to verify the replicability of the method. The second question is used to evaluate whether the precision level of results justifies the effort for computational implementation.

The questions Q1.1, Q1.2, and Q3.1 have three possible answers, i.e., *large extent*, *medium extent*, *minor extent,* and *none*. Meanwhile, Q2 evaluates whether the new method is *worse*, *equal*, or *better than* traditional methods in assessing risks. In turn, Q3.2 offers the choices of *impracticable*, *reasonable*, and *optimal*. Table 16 presents the answers to all questions previously shown. The numbers in the table represent the frequency of the answers, as provided by FRAM experts.

Table 16 - Results of questions

Question	None	Minor extent	Medium extent	Large extent
Q1.1	0	1	2	3
Q1.2	0	0	2	4
	Worse than	Equal than		Better than

Q2	0	1		5
	None	Minor extent	Medium extent	Large extent
Q3.1	0	0	3	3
	impracticable	Reasonable		Optimal
Q3.2	0	5		1

Regarding the effectiveness of the method, the results of both Q1.1 and Q1.2 show that most experts consider the method able to provide useful results beyond promoting substantial improvement to the traditional FRAM. For instance, about Q1.1, E6 stated: *"this method suggests a way to progress with the last FRAM steps, in particular supporting a less-subjective assessment of variability, which is a difficult task, especially in case of limited previous experience with FRAM".* Furthermore, expert E1 said: *"critical activities in the case study, when ranked through the quantitative approach make sense when compared with the previous evaluation employing the traditional FRAM".* The only limitation we have regarding the mathematical model lies in the definition of fuzzy rules. As the method considers the experts' opinions to run a rule-based inference system, this might become a complex and time-consuming task from the point of view of some experts. Even though there are some concerns about mathematical implications, they agree that the method provides precise and useful results and it contributes to supporting FRAM practitioners in assessing risks.

About Q2, all experts agree that the method does not underperform traditional methods (e.g., FMECA, FTA, ETA, HazOp). Experts agreed that the functional map allowed mapping interactions between functions, exposing the analysis to a non-trivial assessment of variability. The integrated system for quantification (i.e. the main novelty of this work) instead complemented the mainly qualitative nature of FRAM, as traditionally applied. Expert E5 stated: *"the relevance of the method is context-dependent. It would be beneficial only when the system's complexity is requiring that level of sophistication. I would discourage the application of this logic when no data can be made available or when the system is purely technical".* This feedback allowed us to understand that, due to their sophisticated structure, the proposed method is most suitable for highly complex systems, or for limited subsets that justify the corresponding resource investment for punctual quantitative assessment. Such systems need robust methods that ensure a higher level of performance when compared to the traditional approaches in supporting the decision-making process.

Concerning question Q3.1, it can be noted in Table 16 that most experts agree the method appears reproducible at least to a medium extent. There are nevertheless some concerns, for example, the number of variables, for which some experts find it difficult to implement the method in a practical.

By analyzing the cost/benefit relation in question Q3.2, expert E4 stated: *"even though at this stage the method looks feasible and applicable, there is a major manual effort to make it operational. As for any method, the benefit/cost ratio would increase in case of the availability of some guided tool to run the analysis"*. According to this expert, this fact might represent a challenge for adopting the method by professional practitioners. We recognize this limitation in our study, thus the comment by E4 allowed us reflecting what methodological weaknesses we need to focus on in the future, and the idea of conceiving a specific software may be a viable solution and a future direction of this research.

4. Discussion

FRAM is a young method, and several scholars have been contributing to its evolution, with multiple approaches, whether qualitative or quantitative. In particular, as seen from the literature, the FRAM has been combined with different semi-quantitative and quantitative approaches (e.g., AHP, Monte Carlo simulation, and fuzzy sets, among others). However, few studies use fuzzy sets to deal with uncertainty from experts' opinions in FRAM analysis. The current study integrated the FRAM with fuzzy sets to examine how the quantified-based perspective would enrich the risk assessment in complex STS. In this way, a general cohesive index was developed to rank critical activities by using FIS.

A comparison with previous studies by Slim and Nadeau (2019, 2020) showed that both can well address the subjectivity of experts' evaluations, but only three linguistic labels are used to categorize the variability while the current study considers five linguistic labels to categorize the magnitude of variability. The greatest advantage of this lies in covering the complete range of phenotypes of the variability, becoming thus more accurate in practical applications. Other previous studies give more attention to evaluating CPCs belonging to each function in the FRAM model (Hirose et al., 2017; Hirose & Sawaragi, 2020), whereas the proposed method is focused on the evaluation of the system couplings. The current approach advocates this standpoint since the couplings usually are intricately interacted, which become them difficult to control because failures in one function will quickly propagate to others (Tan et al., 2017).

Although previous studies that incorporated quantitative tools into FRAM have their own specific merits, most of these studies are confined to quantifying the variability. For instance, they avoid evaluating to what extent the variability is dampened or amplified by the downstream functions. The current study found some clues to overcome this limitation. For example, studies by Bellini et al. (2017) and Bellini et al. (2020) consider the dampening capacity in their evaluations. Nevertheless, while these two studies provide an algebraic manner to calculate the dampening capacity of functions, the current study has the prominent ability to compute them more simply by using a customized FIS, however, without losing the accuracy to cope with the subjectivity of experts.

When referring to prospective analysis, there are many different fuzzy-based methods developed for analyzing the performance of complex STS. For example, cognitive models such as Fuzzy Cognitive Maps (FCM) comprise dynamic methods to structure expert knowledge that aims to collect human perceptions of a particular issue in a graphical presentation (Kokkinos et al., 2018). They use advanced learning techniques aiming to choose appropriate weights for the causal relations between the examined variables (Demertzis et al., 2018). However, the focus on modeling the system considering the causality relationship makes such methods incapable of representing the functions of a system with both technical and human elements (Anvarifar et al., 2017), since the real source of success, as well as failures, is strictly related to everyday work and subsequent performance variability (Patriarca et al., 2017a). Therefore, the FRAM was selected because the authors realized that safety in complex socio-technical systems such as the construction domain would not be improved only by analyzing the causal relationship between elements and providing procedures, and guidelines. Instead, is more reasonable to figure out critical functions through the quantified couplings, since managers can benefit from understanding what function requires more attention.

5. Conclusions

Previous studies have shown that combining FRAM with fuzzy sets may be an effective strategy to improve the shortcomings of traditional FRAM. This study illustrated the usefulness of a novel FRAM-fuzzy framework as a tool for risk assessment in the recycling process of construction waste. This study developed a soft computing method that can be applied in several domains. The proposed framework applies the concept of fuzzy sets to obtain numerical scores for the couplings' response evaluation, which consists of the aggregating magnitude of variability and dampening capacity of functions into a FIS. The rule-based FIS has been enriched with the involvement of the URC configuration, which provided in reducing the overwhelming quantity of rules entailed in traditional approaches. The case study demonstrated that the proposed framework is a useful methodology for quantifying outcomes from FRAM analysis since it helps to cope with the uncertainty and ambiguity of human opinions. The method has been applied to a real example of the recycling process of construction waste, and the decision-making results obtained by the validation of experts prove that the designed method can efficiently handle multiple decision-making experts.

Although this study compensates for drawbacks in the traditional FRAM and some previous studies, there were some limitations that can be further explored in the future. Firstly, for reducing computational effort this study only considered two phenotypes (timing and precision) to categorize the variability of a function, whereas all ten phenotypes could have been considered. While it could have provided an in-depth analysis, this would need additional time for the application. Secondly, in this approach it is supposed that experts have the same importance, so, the method of this paper can be extended by merging FRAM-fuzzy with MCDM methods (e.g., AHP, TOPSIS, ELECTRE, PROMETHEE, etc.). Another limitation refers to the construction of fuzzy rules to the extent new developments for other contexts may imply the need for adapting the inference rules. In this sense, it is worth thinking about exploring other meaningful methodologies to design these rules. Finally, the proposed approach can be extended to different domains and the obtained results can be compared for these different areas.

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Appendix 3

Uncovering resilience abilities in maintenance teams for buildings with Functional Resonance Analysis Method

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Uncovering resilience abilities in maintenance teams for buildings with Functional Resonance Analysis Method

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ABSTRACT
Building maintenance comprises a set of complex socio-technical activities, with many interacting agents. Traditional tools for safety management make the results of such evaluations distant from real situations. Resilience Engineering (RE) argues that improvements in safety performance concern the ability to recognize and adapt to handle unanticipated perturbations. This study aims at increasing the understanding of everyday building maintenance activities for air conditioning systems to uncover resilience abilities developed by the maintenance team to deal with everyday challenges. The Functional Resonance Analysis Method (FRAM) has been applied to model these activities. The data collection comprised interviews and observations. As a contribution, this study outlined the potential of the FRAM model as the basis of an in-depth and systematic analysis of daily performance, highlighting resilience abilities aligned with RE principles.

KEYWORDS
Resilience abilities; FRAM; building maintenance.

INTRODUCTION

The air conditioning systems constitute crucial types of equipment in building infrastructure, as responsible for maintaining good indoor air quality through adequate ventilation with filtration and providing thermal comfort for the building's occupants (Antoniadou & Papadopoulos, 2017). Therefore, adequate maintenance is essential to maintain air conditioning systems running and prevent any hazardous failure that can bring risk to the building's occupants.

In the building environment, the working conditions can all pose challenges to managing safety (Oswald et al., 2018). Also, the workers are exposed to hazards difficult to measure, since the ever-changing workplaces may potentially affect all workers on the site (Rosa et al., 2015). In addition, the absence of a preventive maintenance strategy increases the complexity of the work, once workers need to deal with scarce resources, poor tools, and insufficient teams to cover all the buildings on the university campus. There is a risk of occupational injuries due to the heavy load and physical demands of the activity. Often, mechanics deal with downgraded sites, confined spaces, and hard-to-reach places, especially when the air conditioning devices are installed in the roof or the underground. It is hard to predict or expect how the work will occur, given that work is done daily in different scenarios. Different work situations and emergency scenarios require a variety of responses that prescribed guidelines and procedures are sometimes unable to predict. In this sense, human performance can be understood as flexible and inherently variable (Wahl et al., 2020) that could be allied to cope with demands that complex socio-technical systems require daily.

The traditional safety concept referred to as the Safety-I presumes that things go wrong because of identifiable failures or malfunctions of technological components, procedures, beyond the humans, acting alone or collectively (Hollnagel et al., 2015). This approach is most useful in a system consisting of purely technical elements (Ham, 2020), once assumes it is always possible to identify a linear dichotomic cause/effect relation (Patriarca, Falegnami, et al., 2018) and removing or weakening the causes of adverse outcomes can improve safety (Hirose & Sawaragi, 2020). However, traditional tools in line with Safety-I vision are insufficient to provide a complete and comprehensive representation of the work-as-done (WAD). This stems from the fact that reality is complex, variable, and even unpredictable and working conditions are rarely ideal (Pardo-Ferreira et al., 2020). Such characteristics of Safety-I indicate that the respective approaches should not be used to improve safety in work environments where workers at the sharp end have established safety practices that pervade work activities themselves (Saldanha et al., 2020).

Conversely, the Safety-II vision argues that workers play a significant role in safety management, once human flexibility, and their ability to adjust work to deal with varying conditions instead of strictly following operational rules could contribute to systems working correctly (Lee et al., 2019). Therefore, the safety-II vision encourages a greater emphasis on the aspects that contribute to normal performance (Harvey et al., 2019).

Thus, for reliable analysis and a better understanding of these systems, it becomes necessary to apply a perspective in line with Safety-II and Resilience Engineering (RE), which concerns a new approach for safety management that focuses on how systems anticipate undesirable conditions or managing changes, and thereby to continue the operation, even after a disruptive event, or the presence of continuous stress (Hollnagel et al., 2006).

The resilience abilities have contributed to creating a wide consensus on resilience structure, in which the resilience comprises what the system does rather than something the system has (Patriarca, Bergström, et al., 2018). Hollnagel (2017) defines these abilities as i) monitoring, which concerns developing abilities to cope with near-term events and to monitor what happens in the operating environment; ii) responding, which consists of actions to be adopted to appropriately respond to changes in the system environment; iii) learning, which means an organization modifies or acquire new knowledge, competencies, and skills on everyday work and activities; and iv) anticipating, which lies in attempting to prepare for further events such as disturbances or improvements in the system functioning.

The present study aims to identify emergent resilience abilities in the maintenance activities in line with the four core abilities of resilient systems proposed by Hollnagel (2017). The empirical field of study is a university campus in Rio de Janeiro, Brazil. The analysis was described using the Functional Resonance Analysis Method (FRAM) (Hollnagel, 2012) and outcomes were analysed from the perspective of RE, that is, how the mechanics manage variabilities and disturbances to achieve successful maintenance in their everyday work.

METHOD

The method applied in this research is the Functional Resonance Analysis Method (FRAM) (Hollnagel, 2012), which has been developed under the concepts and principles of the RE. FRAM comprises methodological support for modelling the varieties of the work domain under investigation (Patriarca et al., 2019). Figure 1 presents the framework for analysing empirical resilience abilities, which has three stages.

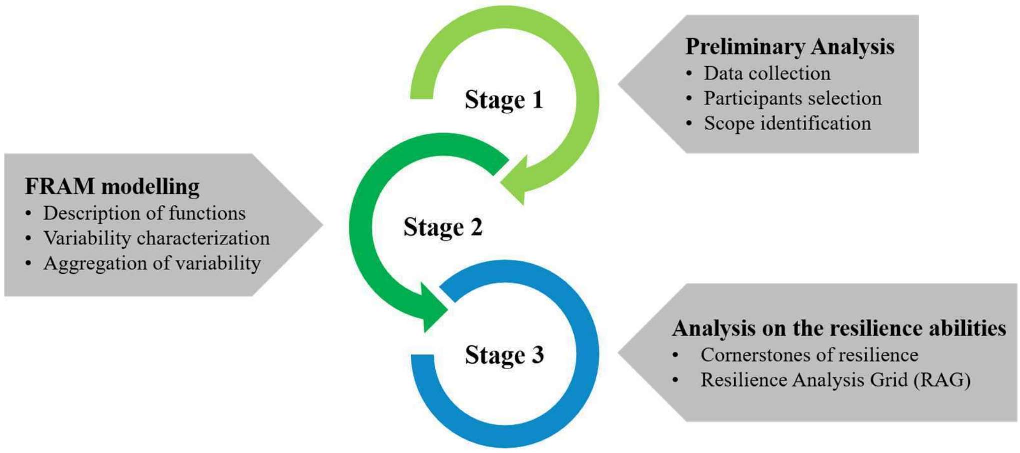

Figure 1. Proposed framework for analysing empirical resilience abilities

Stage 1 is concerned with establishing a preliminary analysis on the common ground where the research was performed. This stage included the scope identification as well as selecting the participants for data collection. The maintenance of air conditioning devices was selected for the study. The main reason for selecting this subject was that it had been part of a recent study (Souza et al., 2021), which made it easier to access for data collection.

Stage 2 is dedicated to a deeper understanding of WAD by using the FRAM. The following is a brief description of the four steps for developing a FRAM model (Hollnagel, 2012). The first step concerns the description of essential functions to perform an activity. These functions can be human, technological, or organizational, depends on its natures in the system. Each function is represented up to six aspects, consisting of one output and five inputs:

- Input (I): what trigger the function or what is processed or transformed by the function
- Output (O): what is the result of the function, it can be either a state change or a specific product
- Precondition (P): mandatory conditions that must exist before the function can be performed
- Resource (R): what the function needs or must consume when it is carried out to produce the result (the output)
- Control (C): what controls and monitors the function to match the desired output
- Time (T): temporal requirements or constraints of the function, regarding both duration and time of execution.

Once the function description is done, the second step is the identification of the output variability of each function of the model, characterising each function with its potential and actual performance variability. After this, a third step consists of examining instantiations of the model to understand how the variability of each function can be resonant in the system. The fourth and last step is the monitoring and managing of the performance variability of each proposed instantiation of the model.

Since the variability analysis in stage 2 is completed, a third and last stage is needed, which a set of questions based on the idea of the Resilience Analysis Grid (RAG) (Hollnagel, 2011) had been used in attempting to categorise empirical abilities captured in each FRAM's function into the four cornerstones of resilience. The definition of general questions applicable to each domain is hardly possible, once resilience is strongly related to the system's purpose for which is being assessed (Patriarca, Di Gravio, et al., 2018). Therefore, it requires the analyst to adjust its structure to the domain-specific context under study (Chuang et al., 2020). Thus, in the current study open questions based on the RAG has been tailored to fit the context of the maintenance in air-conditioning devices.

Data collection and participants

Observations and interviews supported the data collection in the fieldwork. The procedures included direct observation from the work planning meeting of the maintenance team up phase of intervention in air conditioning devices. The open-ended approach had been chosen for the interviews with the participants, in which broad and open questions should be asked, and the replies to them should inform the researcher of the perceptions of the individuals (Sekaran & Bougie, 2016). The objective of the data collection was to gather information to make it easier to understand the tasks that would be subsequently modelled and analysed with FRAM.

Four maintenance workers from the university campus participated in the data collection. Three mechanics trained in split-type air conditioning, and the maintenance supervisor (civil engineer). In everyday activities, the mechanics are responsible for installs, maintains, and repairs of air conditioning devices for all buildings of the organization. The maintenance supervisor plays the role of receiving and analysing requests, issuing work orders (WOs), and offers technical support to the mechanics. The results of the analysis have been validated through semi-structured interviews with workers involved in the study.

RESULTS AND DISCUSSIONS

The purpose of this section is to explore the potential of applying the proposed framework to categorise empirical resilience abilities into the four resilience abilities. A case study is presented in the building maintenance domain, focusing on understanding the WAD in the maintenance of air conditioning devices.

Stage 1 – preliminary analysis

The case study was undertaken on a Brazilian university campus located in the city of Rio de Janeiro. The department for building maintenance is a facilities management unit responsible to maintain acceptable use conditions in the buildings of the campus. The building maintenance covers six areas: electrical, plumbing, air conditioning, civil works, metal works, and carpentry/furniture. The current study is focused on the maintenance of air conditioning devices. Other areas may be disclosed in upcoming studies.

The overall process of building maintenance comprises three major stages: maintenance request, request analysis, and maintenance execution. The current study focuses on the stage of maintenance execution for air conditioning devices. The study on the other stages can be reached in an earlier study (Souza et al., 2021).

Stage 2 – FRAM modelling

The FRAM model for the maintenance of air conditioning systems consists of sixteen functions, as illustrated in Figure 1. Workers who participated in the FRAM development suggested that only eight functions had significant variability: i) check requirements request; ii) choose the best route; iii) triage of WOs; iv) perform customer visit; v) access the site; vi) access air conditioning device; vii) perform repair; viii) register spare parts. Such functions are depicted in green and with a sine wave. Although the variability related to the outputs may be described by using multiple phenotypes, i.e., in terms of time/duration, force/distance/direction, wrong object, and sequence, in this study the two main phenotypes proposed by Hollnagel (2012), i.e., timing (on time, too late, too early, not at all) and precision (precise, acceptable, imprecise) are adopted as they are enough to describe most outcomes.

FMV software (Hill, 2019) allows the graphical display of information and provides useful features to check the completeness of the functions. The construction of a model based on analysis of the everyday work as well as the variability analysis enabled extraction resilience abilities that would contribute to overcoming disturbances throughout the activity.

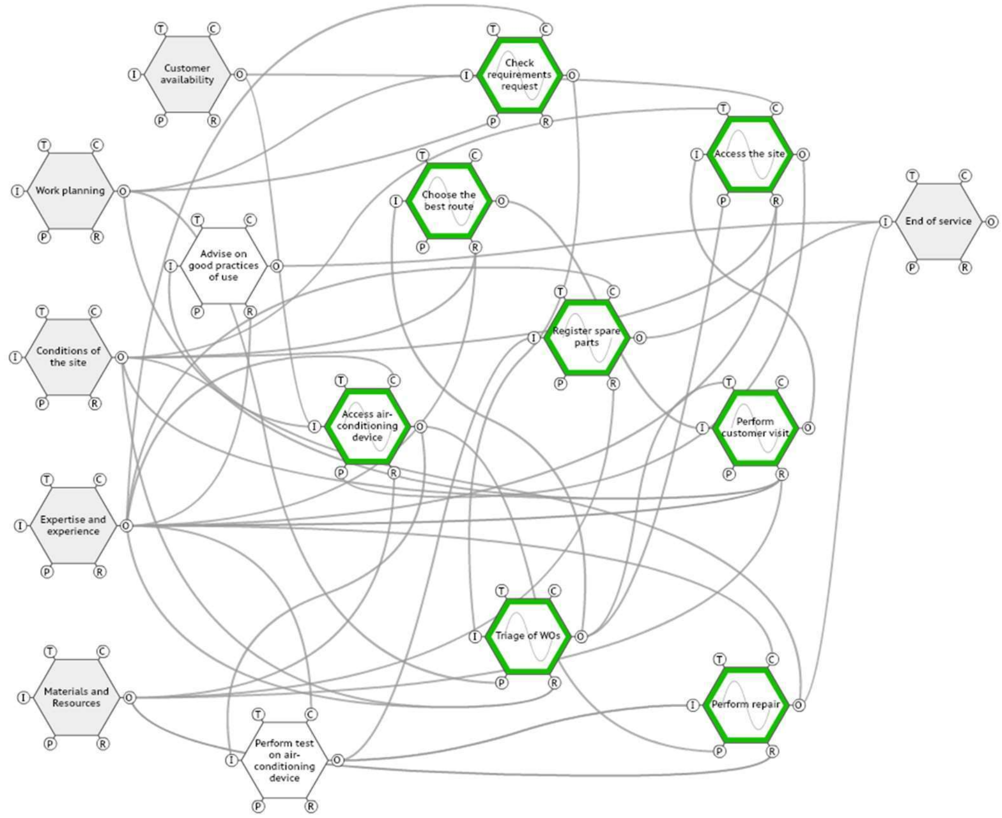

Figure 2. FRAM model for the maintenance of air conditioning devices. Functions depicted in green are functions presenting variability. The other functions depicted in white do not present variability

The function ‘work planning’ represents the planning for daily work. This function requires several decisions made in collaboration with the maintenance team concerning strategies to be adopted during the work shift. The issuance of WOs triggers the function ‘check requirements request’. This study does not intend to explore the issuance of WOs, however can be reached in previous work by Souza et al. (2021). The function ‘check requirements request’ consists of analysing WOs to find the requirements for the maintenance. In this function, mechanics should verify the service requested, the service location, and whether there are any specific demands. As indicated in Table 1, this function relies on the possibility of the check might not occur or might occur with reduced precision. In these cases, it affects the function ‘triage of WOs’, as priorities might be wrongly set.

The function ‘triage of WOs’ represents a cognitive process that happens every morning after meeting with the team. It uses variables mainly the work scope resulting from the function ‘check request requirement’, and resources such as knowledge of the local and time of route as decision-making to prioritize the WOs. As described in Table 1, this function is highly susceptible to variability in both timing and precision. Output quality depends on how thorough the failure description by the requestor is performed. Poor information entails the increase in the possibility of inadequate prioritization of WOs, which may affect the downstream function ‘choose the best route’.

The weather conditions act as a decision element to the function ‘access the site’, e.g., if there is a “heavy rain”, the workers do not perform external services. Conversely, on hot days the workers are exposed to rigorous solar radiation, causing high physical workload and fatigue. To mitigate these effects, when possible, they do not perform activities that expose them to solar radiation in time between 11 am and 3 pm. This setting may lead to variability regarding time faced weather conditions.

Also, functions ‘work planning’ and ‘materials and resources, support technically the performing of visits with WOs and working tools. The output variability regarding precision occurs when the WOs were not issued on time; therefore, the workers need to perform a visit without the WOs at hand.

The function ‘access air conditioning device’ acts as a precondition to the function ‘perform repair’. It also consumes some resources, such as equipment for access (e.g., ladder or scaffolds) because some outside units are installed on the roof or at height. Moreover, the absence of conservation in air conditioning structures is a contributing factor for accidents involving the maintenance team. There are a meaningful number of territories with air conditioning devices installed in places of difficult access or in confined spaces (i.e., devices installed on the roof or the underground) which significantly affect the workers’ performance.

The function ‘customer availability’ is also a temporal constraint to trigger this function because when the customer is unavailable workers cannot access the device to perform the repair. In this case, mechanics use their knowledge to identify near customers requiring maintenance to visit. The function ‘perform repair’ relies on the worker's expertise and experience, mainly regarding the knowledge they have on the specific device. Moreover, this function consumes several resources, such as working tools, an oxyacetylene torch, a vacuum pump, among others. Indeed, the number of resources depends on the work scope. In some cases, workers need to return to the workshop to get additional tools to perform the repair once WOs do not provide the work scope properly. As presented in Table 1, the potential variability regarding both timing and precision in the function 'perform repair' depends on spare parts availability and working tools.

The background function 'expertise and experience' controls the triggering of the 'register spare parts' function once the mechanics' expertise is crucial to perform the task. This function consumes resources as a standard form used by the mechanics to record the spare parts. As shown in Table 1, whereas output variability regarding time is "on time", variability regarding precision is "imprecise". The imprecise output results from the unavailability of the standard form to record spare parts. Mechanics need to appeal to the memory or a handwritten paper to record parts. However, these actions can lead to misunderstandings.

Table 1 summarizes the functions presenting variability as well as the characterization of output variability in terms of timing of precision. The interactions among functions had been graphically indicated in Figure 1, which shows the instantiation of the FRAM model for the analysed scenario.

Table 1. Variability analysis on the instantiation of the FRAM model

Function	Variability	
	Regarding time	Regarding precision
Check request requirements	Not at all If available information to work is poor, the output may not be performed at all.	Imprecise In the event of an incorrect or incomplete failure description by the customer, there may be an error in the analysis.
Triage of WOs	Too late This function is highly dependent on workers' expertise.	Imprecise Output quality depends on how thorough the requestor information is. Therefore, some WOs may be wrongly prioritized because of poor information from the requestor
Choose the best route	On-time This function comprises the decision-making of the team. It is a function relatively quick.	Acceptable Output precision depends on the workers' knowledge in the territory.
Perform customer visit	Not at all This function depends mainly on the weather conditions.	Imprecise Non-issuance of WOs can lead to execution error due to lack of information regarding work
Access the site	Not at all If the customer is not at the site or unavailable, the output may not be produced at all.	Acceptable Output precision depends on the workers' knowledge in the territory
Access air conditioning device	Not at all If the conditions for performing the maintenance are adverse, the output may not be performed at all.	Imprecise Quality of access to air conditioning devices depends on the conditions of the site (e.g., device installed in high outside position, confined space, or in the roof). These conditions may cause risky situations for workers or imply non-perform of the maintenance.
Perform repair	Not at all It depends on spare parts availability. If there is no spare part to perform repair, the output may not be performed at all.	Imprecise All the outputs depend on how thorough the tasks are performed.
Register spare parts	On-time Mental effort consumes relatively little time related to the activity.	Imprecise Unavailability of the form to record spare parts can lead to misunderstandings or errors.

Stage 3 – analysis on the emergence of resilience abilities

Table 2 presents the relationships between the functions, the resilience abilities that emerged from the field examination, and the four cornerstones of resilience. The four cornerstones were brought into this analysis in attempting to categorise the empirical abilities captured in each analysed function. From the variability analysis, a set of questions based on the idea of the RAG had been developed to determine how each empirical ability matches the four cornerstones of RE.

As shown in Table 2, the same empirical ability may be noticed in multiple functions. For instance, the knowledge of the territory and specifically the site where the work is done can be encountered simultaneously in more than three functions. Similarly, these empirical abilities seem to be associated with multiple core abilities depending on how they are employed.

The analysis disclosed that mechanics take advantage of their expertise and experience to interpret data from WOs. Also, when complete data are not available, they go to the site and check requirements *in-loco*.

The prioritization of WOs is supported by the workers' tacit knowledge. This decision-making relies mainly on the workers' knowledge about the territory they operate. The knowledge of the territory is a crucial element in delineating an optimized route to avoid unnecessary pathways.
The function 'perform customer visit' takes advantage of the expertise and experience of workers, such as workers' knowledge on the territory, and affinity with customers, this contributes to imitate an appointment. In this scenario, we could note that some WOs are issued verbally on the site by the mechanics. The supervisor reported that flexibility is vital to respond to unscheduled situations quickly, i.e., this variability enables the attending faster in specific demands (e.g., lack of energy and water leakage) or to optimize the route of workers. In this sense, at the operational level, resilience may be a function of how organizations deal with apparently contradictory requirements, i.e., good procedures and good plans are desired, while appropriate flexibility is encouraged to meet the real demands of the daily operation (McDonald, 2006).
The function 'access the site' is the reason for many complaints by the workers. The function 'customer availability' controls the decision-making about aborting or perform the repair. We noted some cases that on arrival at the site, the team did not find anyone to receive them. Faced with this situation, usually, they either visit another customer or return to the workshop. Also, the function 'access the site' uses resources like workers' expertise, i.e., the knowledge on specific conditions of the site to support the decision-making during the activity.
The situational context, e.g., the weather and site conditions are constantly changing and can be the source of small and big surprises (Siegel & Schraagen, 2017). Therefore, the ability to learn from past experiences and anticipate actions perform a crucial role in safe maintenance operations.
As aforementioned, the instant of accessing the air conditioning poses occupational risks to the maintenance team as well as exposes them to hazards. To overcome these constraints, the maintenance team makes sense on the current conditions to construct safety during their maintenance interventions. Thus, sensemaking (Weick et al., 2005) contributes to resilience since it focuses on sharp-end adaptations (Kilskar et al., 2018) for safer decisions, but also ways to have efficiency in the maintenance.
In providing a bill of materials, the procedures and guidelines provide that a standard form should be used for it. However, in the WAD this form is unavailable most of the time. When faced with it, the mechanics proposed to create a group in the messaging app to share relevant information about the WO. To perform the repair in the devices sometimes mechanics faces the unavailability of spare parts. However, workers adopt some strategies to cope with these constraints, as dismantling an old device to remove a part in-condition of use.
This study proposed an integrated framework that brings the four cornerstones of the RE into building maintenance practices. As previously stated, some questions inspired in the RAG were adopted, such as, does the maintenance team try to learn from failures (things that go wrong) as well as from successes (things that go right)? Also, how they cope with incomplete information? To check requirements on the WOs, sometimes the maintenance team deals with poor description for the failure in air conditioning devices. However, the mechanics have developed resilient abilities to deal with the specific demands of their activities, making use of the variability positively. For example, knowledge acquired from previous experiences contributes to interpreting data in WOs even though the available information has a high degree of subjectivity. Moreover, the workers' sensemaking on current conditions arises in the instant of accessing the air conditioning device; thus, they choose the better procedure to gain access to the device.

Table 2. Resilience abilities uncovered with the FRAM modelling

Function(s)	Description of resilience abilities	Cornerstones of resilience			
		Anticipating	Learning	Monitoring	Responding
Check requirements request	To check requirements in WOs, the mechanics engage their abilities to interpret data based on the past experiences		✓		✓
	Mechanics check *in-loco* the requirements for the maintenance when complete data has not been previously made available				✓
Work planning	Strategies to be adopted during the work shift are chosen in a daily work planning	✓			
Choose the best route / Triage of WOs / Access the site	The knowledge on the territory supports the decision-making in delineating an optimized route to visit the sites	✓	✓		✓
Perform customer visit	The relationship and affinity with the customers contribute to speeding up the service and overcoming limitations on missing information		✓		✓
	Workers monitoring the weather conditions to decide on the maintenance schedule			✓	
	Emergencies require WOs to be issued verbally on the site by the mechanics				✓

Access air conditioning device	Knowledge of the site and specific conditions supports the procedures to be adopted in the maintenance task		✓		
Perform repair	To overcome unavailable spare parts, mechanics maintain in the warehouse parts in-condition of use	✓	✓		
Register spare parts	Mechanics proposed to create a group in message app to facilitate sharing relevant information about the WOs when the fieldwork is in progress.			✓	

CONCLUSION

This article suggested a framework to identify empirical resilience abilities and check the adherence of them to the four cornerstones of resilience. This study used the FRAM to model routines in building maintenance for air conditioning of a Brazilian university campus.

The major finding in this study stem that the mechanics lack accurate information on current conditions to perform their activities. Nevertheless, knowledge of the territory seems to be a prerequisite for successful operations. Thus, the most visible manifestations of resilience in the maintenance activities are resulting of adaptability and sensemaking of the maintenance team.

The case study demonstrated that the FRAM model might offer empirical evidence for extracting resilience abilities from variability analysis. Moreover, questions based on the idea of RAG proved to be an effective means for categorising empirical resilience abilities into the four cornerstones of resilience. However, future studies are required to explore opportunities, such as i) examination of this framework in other domains, ii) a quantitative analysis of resilience from the FRAM modelling, and iii) developing of strategies and guidelines to enhance empirical resilience abilities.

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Appendix 4

Resilient performance in building maintenance: a macro-cognition perspective during sudden breakdowns

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Abstract

Building maintenance encompasses multiple tightly inter-connected agents (e.g., technicians, occupants, supervisors, and equipment). Variable working conditions and limited resources may affect the safety and sustainability of the activities. Although recent studies have explored how complex systems can perform resilient behavior in facing the complexity of everyday activities, the factors that effectively contribute to resilient performance are still paired with limited empirical evidence. We studied the performance of the maintenance team during sudden breakdowns of air-conditioning devices in a large university campus, using the Functional Resonance Analysis Method (FRAM). A FRAM diagram containing 30 functions was organized including six macro-cognitive functions (expertise, sensemaking, communication, coordination, collaboration, and adaptation/improvisation), examining their role in anticipating, and responding to emergencies, and eight functional units that are directly impacted by disturbances were analyzed in more detail. Results indicate that macro-cognitive functions can greatly impact the functionality of the maintenance team in pursuit of their goals. Moreover, we noted those macro-cognitive functions here analyzed depend on each other to produce resilient performance.

Keywords: FRAM; resilience engineering; building maintenance; macro-cognition; air-conditioning; HVAC

1. Introduction

The maintenance of buildings concerns maintaining their components and systems in order to ensure proper functionality during the operation phase of buildings (Horner et al., 1997; Ruparathna et al., 2018), once reducing the impact of structural degradation, driven to extend the lifespan of the buildings (Khalid et al., 2019). The functional structure usually includes air-conditioning installation and maintenance work, welding, carpentry/furniture, fire services, electrical wiring, plumbing, and drainage, among others (Chan et al., 2020; de Souza et al., 2021).

The operational regime of the buildings creates a dynamic environment and complex organizational structure, which constantly exposes their workers to varying and unexpected safety risks such as the risk of falls, bruises, cuts, etc (Akanmu et al., 2020) and contributes to becoming maintenance more labor-intensive, and costly in their operational stages (Asmone and Chew, 2020). Systems are often called complex whenever is difficult, or even impossible, to reduce the number of components to understand fully the behavior of the system as a whole (Pavard and Dugdale, 2006). It means that each component responds locally to information presented by them and does not know the full effects of its actions (Dekker, 2011).

In building maintenance, each maintenance technician performs varied and challenging tasks which include working at height, in confined working spaces, limited time, intense interaction among different agents, ever-changing workplaces, and sometimes under adverse weather conditions (Pilanawithana et al., 2022). Such conditions expose workers to risky situations and contribute to the emergence of complexity (de Souza et al., 2021). The lack of effectiveness of Information Technology (IT) systems in supporting maintenance decision-making poses difficulties to perform crucial activities since it does not fully support the mental activities accomplished to perform such activities, which include failure analysis, documentation of maintenance, fault location, repair, and reconstruction. Moreover, in public institutions, maintenance activities suffer from financial and labor resource scarcity (Alves Tenório de Morais and Casado Lordsleem Júnior, 2019). Organizational aspects, such as constant pressures for productivity, aligned with the growing application of new technologies (e.g., sophisticated air- conditioning systems, new automated systems, etc.), also increment the complexity of such activities (Souza et al., 2021). The nature of such activities requires effective organizational safety management strategies.

The classical safety management strategies are usually based on the degree to which the risks are known or can be made known (Pilanawithana et al., 2023). Nonetheless, in modern socio-technical systems, conventional tools are insufficient to provide a complete and comprehensive representation of the work-as-done (WAD). This stems from the fact that reality is complex, variable, and even unpredictable, and working conditions are rarely ideal (Pardo-Ferreira et al., 2020). Such characteristics indicate that these approaches should not be used to improve safety in work environments where workers at the sharp end have established safety practices that pervade work activities themselves (Saldanha et al., 2020). Therefore, Resilience Engineering (RE) approach has been proposed as a discipline to address the limitations of traditional techniques for managing safety, since it promotes a holistic perspective to ensure systems are prepared for, cope with, and recover from any disorder in dealing with situations involving uncertainty, time pressure, and negative consequences (Steen et al., 2022). The Functional Resonance Analysis Method (FRAM) (Hollnagel, 2012) is one of the main methods that seems to be getting most attention from the Resilience Engineering community in the past few years (Patriarca et al., 2020). It has been widely used to visualize complex systems' operations based on performance variability.

1.1 Research problem

FRAM is recognized for its wide range of contexts and different applications from accident analysis to safety management, as illustrated in extensive literature reviews (Patriarca et al., 2020; Salehi et al., 2020). Moreover, FRAM has been used to understand the potential source of resilience and brittleness in complex systems, as explored in recent applications (Bjørnsen et al., 2020; Bueno et al., 2021; Smith et al., 2020). Although FRAM has demonstrated its efficiency in recent applications, it does not provide ways to analyze or evaluate the overall resilient performance of an organization (Saldanha et al., 2022).

Recent studies (Bueno et al., 2021; Pettersson et al., 2022; Son et al., 2020b) have explored how complex systems can perform resilient behavior in facing the inherent complexity of daily activities. Furthermore, there is evidence (Amodeo and Francis, 2019; Bergström and Dekker, 2014; Pawar et al., 2021; Vert et al., 2021) suggesting that cognitive processes play a pivotal role in the system's resilience. However, empirical evidence on what factors effectively contribute to sharp-end operators' resilient performance remains underexplored in the literature. Fig. 1 presents assumptions on the interactions of the macro-cognitive functions and resilient performance addressed in this study. We examine the role of macro-cognition on the resilience of maintenance operations in buildings by investigating the following question: Do the macro-cognitive functions improve the ability to anticipate, and to respond to emergencies and if so, how?

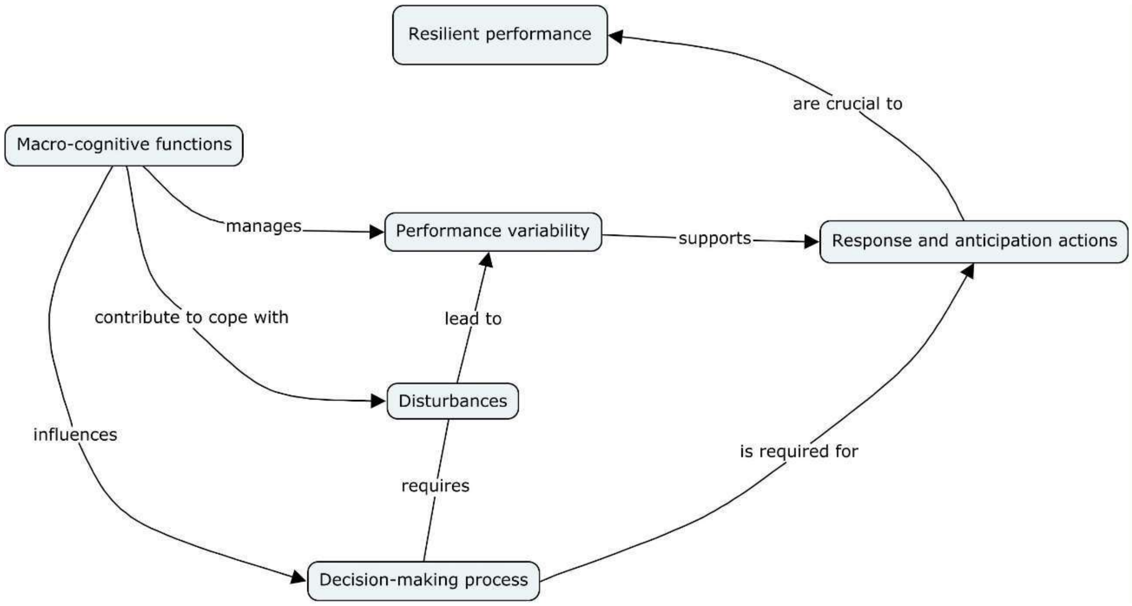

Figure 1 - Potential interaction between macro-cognitive functions and resilient performance

1.2 Research aim

In order to understand the factors that contribute to resilient performance of complex systems during stressful situations, a functional approach seems required. In its traditional structure, FRAM defines a model showing the interactions among functions, and defining the system variability. Following this idea, the aim of this study is to propose a FRAM structure that enable us to examine how the macro-cognition affects the resilience of operations. Starting from a previous study (Souza et al., 2021), a FRAM model was developed in the maintenance for the sudden breakdowns in air-conditioning devices for this purpose. To the best of our knowledge, it seems that macro-cognition has not previously been explored by using the FRAM. Then, the current study could serve as an appropriate theoretical lens for better support maintenance practitioners by redesigning maintenance processes as well as developing a cognitive skills training to improve resilience capabilities, such as responding and anticipating.

2. Theoretical foundations

2.1 Resilience Engineering

Resilience Engineering (RE) research paradigm provides an alternative approach to deal with the limitations of traditional safety management systems (Hollnagel et al., 2006). RE argues that people alone or collectively need to adjust their performance to respond to match operating conditions and safety risks associated with the complexity of socio-technical systems (Hollnagel, 2015). Hollnagel (2018) has developed four resilience potentials (responding, anticipating, monitoring, and learning) to characterize resilient systems. Responding refers to actions to appropriately deal with disruptions in the system environment. For example, a sudden breaking down of an air-conditioning device requires an appropriate response to restore its availability. Anticipating comprises the attempt to prepare for further events such as disturbances or improvements in the system's functioning. Monitoring concerns developing abilities to cope with near-term events and to monitor what happens in the operating environment. Monitoring capabilities are crucial to enable people to appropriately respond to abrupt changes in the system and anticipate future states. Learning means an organization modifies or acquires new knowledge, competencies, and skills from both positive and negative daily experiences.

2.2 Macro-cognition

Naturalistic decision-making (NDM) is the term used to describe decision-making in real-world settings, as opposed to laboratory environments (Klein, 2008). Klein (1993) described how people were able to make decisions under time pressure and uncertainty in developing the Recognition Primed-Decision (RPD) model (Klein, 2008). The RPD model states that experts normally draw on their previous experience to recognize the situation, set expectations, define priorities, and select a course of action. In limited-time situations, for example, making decisions by recognizing patterns is more efficient than comparing multiple alternatives to achieve the optimal outcome (Klein, 2015; Zhu et al., 2021). Nonetheless, RPD focuses on the individual level, and it does not cover the team aspect and its influence on individual decision-making (Steen and Pollock, 2022).

Recently, the NDM community has expanded its perspective to cover the analysis of macro-cognition and to perform naturalistic studies of cognitive processes and variables (Klein and Wright, 2016). Macro-cognition describes mental activities/cognitive work that are performed by individuals, teams, and technological systems in complex conditions, under situations of uncertainty and competing goals (Fiore et al., 2010; Klein et al., 2003; Ward et al., 2018).

Macro-cognition is a concept that covers a broader and interrelated set of cognitive functions at the team, organizational, and individual levels (Klein, 2008). For instance, Klein et al. (2003) adopted six functions to describe the macro-cognitive system including planning, problem detection, coordination, naturalistic decision-making, sensemaking and situation assessment, and adaptation/re-planning. Patterson and Hoffman (2012) adapted the Klein et al. model (2003) for space shuttle missions and proposed an integrated macro-cognitive model for the primary functions of detecting problems, sensemaking, re-planning, deciding, and coordinating. Our theoretical foundation encompasses six macro-cognitive functions: sensemaking, expertise, adaptation/improvisation, coordination, collaboration, and communication, which are defined in Table 1.

In the current study, "re-planning" was replaced by "adaptation/improvisation" since this latter sounds more familiar with key constructs that have been used in RE research. While re-planning and adaptation/improvisation have common attributes, nuanced differences also exist. First. re-planning implies recognizing that a priori planned activities did not occur as expected. It means that, as constraints are unveiled, tasks are flexibly adapted to the current conditions (Patterson et al., 2020). Second, adaptation/improvisation can be seen as the capacity to respond to expected and unexpected events and manage disruptions (Steen et al., 2021). Such measures are those prescient ones that enable the system to adapt to the variable environment, usually taken temporarily or periodically (Li et al., 2019b).

Previous models (e.g., Klein et al., Patterson and Hoffman) adopted coordinating as the process of orchestrating the sequence and timing of interdependent actions among team members (Marks et al., 2001). However, as pointed out by Whaley et al. (2016), coordinating is part of a larger macro-cognitive function, i.e., teamwork, that is specifically characterized by synchronizing goal-directed behaviors in interdependent activities (Salas and Cannon-Bowers, 2001). Teamwork is unfolded in three independent functions to represent the coordination, collaboration, and communication among team members (Whaley et al., 2016). In the present study, such functions are adopted to examine their contribution to system resilience.

Expertise was adopted as a macro-cognitive function as overlapping the "deciding" function (Patterson et al., 2020). This study was not specifically interested in addressing how professionals make decisions in operational settings, which can be retrieved from other studies, e.g., Fogaça et al. (2022). Rather, the current study aimed to examine to what extent expertise contributes to assertive decision-making for anticipating and responding to sudden breakdowns.

Table 1 – Macro-cognition functions and definitions

Macro-cognitive function	Definition
Sensemaking	The sensemaking process is based on creating a mental representation (mental model, story, schema, script, etc) that links data with other elements to explain and describe the relationship of the data with other entities (Klein et al., 2007). In addition, it provides meaningful clues to an event or situation in a given context without being influenced by the availability of choices (Weick et al., 2005).
Expertise	Expertise comprises one of the primary psychological and human factors that impacts the understanding of people on their environment (Whaley et al., 2016). It is an attribute of an individual or group of individuals that affects their reliability and quality of performance when interacting with a system (Farrington-Darby and Wilson, 2006).
Adpatation/improvisation	Adaptation and improvisation are concepts often used interchangeably (Grøtan et al., 2008; Son et al., 2020a), although some differences are pointed out. Adaptation is close to general changes in the system regarding the allocation of resources whereas improvisation comprises the spontaneous and creative process of attempting to achieve an objective in a new manner (Vera and Crossan, 2005). In other words, it relates to adaptation to changing situations that present unexpected and unplanned demands on a team where new responses need to be executed promptly (Lundberg and Rankin, 2014).
Coordination	Coordination can be described as the phenomenon that concerns how a system is ordered spatially and temporally, in functional ways (Wiltshire et al., 2019). In addition, "it includes managing interdependencies of activity and communication across individuals acting in roles that have common, overlapping, or interacting (and possibly conflicting) goals" (Patterson and Hoffman, 2012).
Collaboration	Collaboration is a cognitive skill pervasive in many human interaction contexts ranging from everyday life to highly complex work environments (Wiltshire et al., 2019). It refers to how members of a team work together to generate solutions for problems (Fiore et al., 2010; Whaley et al., 2016).
Communication	Communication is a reciprocal process concerned with the exchange of information between different team members clearly and accurately in a prescribed way (Zhang et al., 2023). It is an attribute ubiquitous in teamwork, i.e., coordination and collaboration (Whaley et al., 2016), and in natural settings, team members engage in communication through mechanisms such as verbal, nonverbal, textual messages, and symbol-based language (Keyton et al., 2010).

3. Materials and methods

This section provides information on research setting and procedures for collecting and analyzing data, and it defines the FRAM as the basis of this approach. Additionally, the section explains how the FRAM application supports the macro-cognition analysis, as proposed in the introductive section.

3.1 Research setting

The study was conducted in a Department for Building Maintenance (DBM) for a university campus in the city of Rio de Janeiro, Brazil. This institution is the largest engineering education and research canter in Latin America, consisting of 13 graduate programs in engineering. Overall, the DBM consists of facilities with responsibility for maintaining the building infrastructure. At the time of data collection, beyond the services for HVAC systems, it included welding, carpentry, fire services, electrical wiring, plumbing, and drainage, among others. The adopted maintenance strategy is mostly reactive and includes cleaning operations to remove debris and contaminants, localized repair and minor parts replacement, minor repair to mitigate the degradation process of the infrastructure, and major interventions to correct more serious anomalies or even replacement of vital components.

3.2 Data collection

Data collection was conducted following an ethnographic approach (Emerson et al., 2011). As suggested by Tutt and Pink (2019), this type of design allows researchers to explore the local circumstances in such ways that they can get under the surface of what appears to be happening and offer a comprehensive understanding of a complex phenomenon that may lead to new insights and understandings. Procedures included direct observation, as well as semi-structured interviews with the technicians on topics like work order analysis, repair, and safety. Informal conversational interviews during operations were also recorded and considered for analysis. Additional sources of data included analysis of documents, such as work order data sheets, and maintenance record documents. The use of this mix of data collection techniques made it possible to capture different perspectives of the same phenomenon.

Participants spanned one supervisor and three technicians, who specialized in the maintenance of air-conditioning devices. On average, participants had 10 years of working experience in the HVAC maintenance domain. The research effort comprised non-participant ethnographic observations that were conducted by the first author over two months. In all, twelve sessions of observations were completed across the participants on different weekdays and shifts. The main objective was to understand normal operations during maintenance activities. Observations focused on stages of work order analysis, preparation for repair, team meetings, and general maintenance activities, as well as the coordination of events like sudden breakdowns in air-conditioning devices.

The observations were carried out in the locations in which they naturally occurred, at varying times of the day, in order to capture the variability of the work. The researcher recorded extensive field notes of both observed events and insights from the observations.

Additionally, semi-structured interviews in approximately 18 hours were conducted in person with the four participants. Interviews were conducted whenever the researcher had the opportunity to enquire about the workers' activity. An open-ended approach was chosen for the interviews to make emerge more easily the perceptions of the individuals (Sekaran and Bougie, 2016). Thus, participants were asked to describe the challenges and factors that influence the maintenance operation, including their decision-making process to overcome limitations and constraints in the work. Moreover, the interviews included the opinions of technicians and the supervisor about what constituted a successful operation to recovery an air-conditioning device, as well as how they coordinated activities between themselves and how the information was shared. Participants' perspectives presented in the interviews were used by validating what was observed to identify core functions, specific aspects, and performance variability related to each function, which were the basis for the FRAM modeling.

The first meeting started by introducing the maintenance supervisor to the aim of the study, as well as the procedures to be adopted during the fieldwork. At the same opportunity, technicians working with air-conditioning devices were personally invited to participate in the research activity. Participants were asked if they were willing to be shadowed and were invited to ask questions during the accomplishment of activities. All participants agreed, and thus informed consent was obtained. In addition, they were instructed to naturally perform their activities, and provide information spontaneously written or verbally, dependent on their preference.

During all subsequent visits, the researcher was allowed to follow up on incoming calls, as well as the role of the maintenance supervisor in coordinating tasks from the maintenance office. Likewise, the researcher engaged with technicians during operations in the field, but it should be noted that it was not possible to access settings with apparent hazards. Furthermore, the researcher informally engaged with technicians before and after the work shift. The data collected at this source consisted of descriptions of what had been observed and expressed by the participants. This enabled the researcher to be close and familiar with technicians and proved to serve as a valuable data source that enhanced the researcher's view of the organizational characteristics of the participants and revealed issues that were not possible to identify by the observations at work.

3.3 Data analysis

Data collected in the previous stage were analyzed in a structured manner based on FRAM. Firstly, core functions were identified and represented in a tabular format. Then, the variability and disturbances noted were described and linked to the corresponding function. Hence, the researcher outlined a graphical FRAM representation to show the current model of functions for the management of operations for the sudden breakdowns of air-conditioning devices. Participants were invited to validate and provide additions to the model.

Afterward, the analysis of the macro-cognition was undertaken using three iterative phases of the content analysis method proposed by (Krippendorff, 2018). In phase one, six pre-defined themes were considered, which refer to macro-cognitive functions, as previously mentioned in sub-section 2.2. In phase two, the researcher analyzed and manually coded records of interviews, field notes of observations, and document analysis. Thus, when analyzing these data, the researcher gathered excerpts of raw textual data that could support the identification of information related to the six macro-cognitive functions. Then, the conceptually similar codes were iteratively revised and adjusted as necessary. Lastly, in phase three, the relationship between extracted codes from raw data and macro-cognitive functions was iteratively examined. Moreover, the researcher provided a brief explanation of the macro-cognition to participants, and then, they were invited to give their view on what category of macro-cognition contributed to anticipating and responding to some disturbance. Participants were invited to suggest potential strategies for improving the resilience of the operations. Several rounds of reading raw textual data, interpretation, and validation with participants were needed to construct the FRAM model integrated with macro-cognitive functions, as well as to identify how those were linked to resilient actions, particularly in anticipating and responding to disturbances during specific events.

3.4 Functional Resonance Analysis Method (FRAM)

The Functional Resonance Analysis Method (FRAM) (Hollnagel, 2012) has been adopted as a method to functionally describe socio-technical systems, couplings among functions, and their performance variability, as well as analyze how such variations may spread throughout the system and how it may adapt to keep performance within the required parameters (Clay-Williams et al., 2015; Li et al., 2019a). This methodology is based on four principles:

- Equivalence of failures and successes: Failures and successes occur in much the same way.
- Principle of approximate adjustments: People typically adjust their everyday performance to overcome disruptions and underspecified working conditions of the socio-technical systems due to the impossibility of prescribing tasks and procedures in detail.
- Principle of emergence: It is not possible to predict some events at work. Many events appear to be emergent rather than resultant from a combination of fixed conditions. These events may lead to results that cannot be explained just by a cause-effect relationship of the operation of specific components or parts.
- Functional resonance: it represents the detectable signal emerging from the unintended interaction of the everyday variability of multiple signals. These signals may mutually affect each other, leading to either positive or negative outcomes. These outcomes are difficult prognoses and significant uncomfortable management.

To perform a FRAM analysis, it is necessary to follow four steps, as indicated by Hollnagel (2012). The first step includes identifying and describing functions, that can be characterized up to six aspects (input, preconditions, resources, time, control, and output). These functions can be classified as background or foreground functions. Background functions require a single input or one output and constitute the boundary of a system. Foreground functions are used for the main analysis and require a complete definition of all six aspects, when possible (Sujan et al., 2022). The six possible aspects to describe a function are detailed, as follows:

- Input (I): It is what triggers the function or what is processed or transformed by the function.
- Preconditions: mandatory conditions that must exist before the function can be performed.
- Resources: what the function needs or must consume when it is carried out to produce the result (the output).

- Time: temporal requirements or constraints of the function, regarding both duration and time of execution.
- Control: what controls and monitors the function to match the desired output.
- Output: what is the result of the function, it can be either a state change or a specific product.

The second step is the characterization of the output variability of each function that constitutes the FRAM model. One simple way of describing the variability of the output of a function is based on time and precision. The third step focuses on determining the possibility of functional resonance based on couplings among functions and their potential/actual variability (Salehi et al., 2021). Hollnagel (2012) suggests that looking for functions with multiple couplings may be a first step in determining whether functional resonance can occur. The fourth and last step in the application of FRAM is the monitoring and managing of the performance variability. The most efficient strategy to manage the variability is to adopt actions that either dampen the negative effects or reinforce positive effects (França et al., 2020).

3.5 Macro-cognitive analysis supported by Functional Resonance Analysis Method (FRAM)

In this subsection, we explain how the macro-cognitive functions are integrated into the FRAM structure to examine their contribution to resilient performance. A graphical representation of the developed methodology is shown in Fig. 2.

In **Step 1**, a preliminary analysis was conducted to obtain general knowledge about the organization and to define the boundaries of the system under analysis. It included the analysis of the organizational strategy, process flows, workers, and physical structure. **Step 2** was concerned with the construction of the FRAM model. Following three of four steps of the FRAM, we were able to first build a FRAM instantiation, focusing on the maintenance operation in air-conditioning devices during sudden breakdowns. To this end, we used data collected by observations and interviews to construct a graphical representation of the key functions and their couplings using the FRAM Model Visualiser (FMV). Several rounds of discussions were needed to validate the accuracy of the functions' descriptions. It also comprised the understanding the variability and disturbances related to each function, as well as the understanding how such variability unfolded during maintenance operations. Lastly, rather than proposing recommendations to manage the variability, **step 3** was concerned with analyzing macro-cognitive functions and their contribution to the anticipation and response to sudden breakdowns which was done from the interaction of such functions with the functional units. Thus, from compiling the data gathered in the previous steps, a comprehensive FRAM model was obtained including those functions in the system.

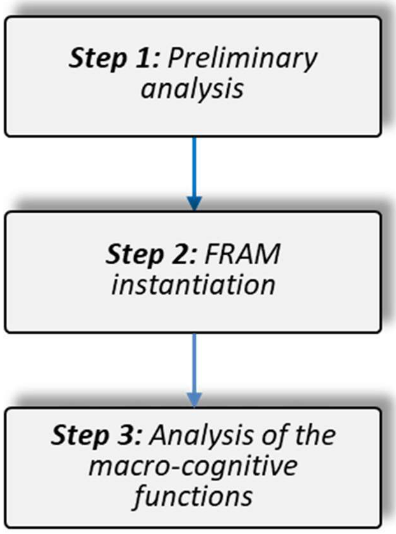

Figure 2 - Framework of analyzing macro-cognition from the functional perspective

4. Results and discussions

4.1 Preliminary analysis of the maintenance operations (step 1)

The maintenance operations for air-conditioning devices have been conceived for typically low demand. In this context, most problems can be solved in two to four days, and installation is acceptable to be solved in more than four days, but usually in less than one week. However, in summer, when the HVAC is used to provide cooling air, demands for maintenance due to malfunctions potentially increase which impacts usual operations. The scenario selected for this analysis comprises maintenance operations during the response to sudden breakdowns in air-conditioning devices.

Most devices used at university buildings are ductless split type. This type of air-conditioning device consists of an outdoor unit that provides hot or cold refrigerant into the building to one or more indoor fan units. The indoor units contain a fan that blows air over the refrigerant-filled heat exchanger, and hot or cold air is distributed throughout the room (Bhandari and Fumo, 2022). Such devices normally embed advanced technologies which require well-trained and qualified personnel to maintain them (Balaras et al., 2007). At DBM, the maintenance supervisor supports the team and provides aid to customers (namely occupants). In turn, technicians are responsible for detecting and dealing with operational demands, installing devices, and repairing as requested. To this end, they need to go to the site of a specific device and perform the maintenance task.

4.2 FRAM instantiation (step 2)

The FRAM model for the instantiated scenario is shown in Fig. 3. An instantiation of a FRAM model represents a particular set of functions mutually coupled under specific situations (Sujan et al., 2022). Mapping the maintenance operations revealed 30 functional units. Some of these functions were classified as foreground functions or background functions according to their relevance. Of these 30 functions, the model revealed 10 were background functions, and 20 were foreground functions. The maintenance supervisor performs 8 functions, that are marked in green, whereas HVAC technicians perform 12, that are marked in purple. Macro-cognitive functions are marked in blue. Although the 6 macro-cognitive functions were categorized as background functions, they were considered to be crucial functions, especially in critical situations and emergencies. Additionally, despite all functions being equally important for the construction of this FRAM model, in the opinion of the workers, some of these are often affected by disturbances during emergencies.

Table 2 details 8 functions that are directly impacted by exogenous/endogenous disturbances, as reported by the personnel involved in the study. It also depicts the relationship between FRAM functions and macro-cognitive functions, beyond the resilience strategies adopted to cope with disturbances. The potential disturbances were modeled as stemmed of output variability from upstream functions, or as ones that emerge from within the reference function. On the other hand, resilience strategies are proposed that can mitigate these disturbances.

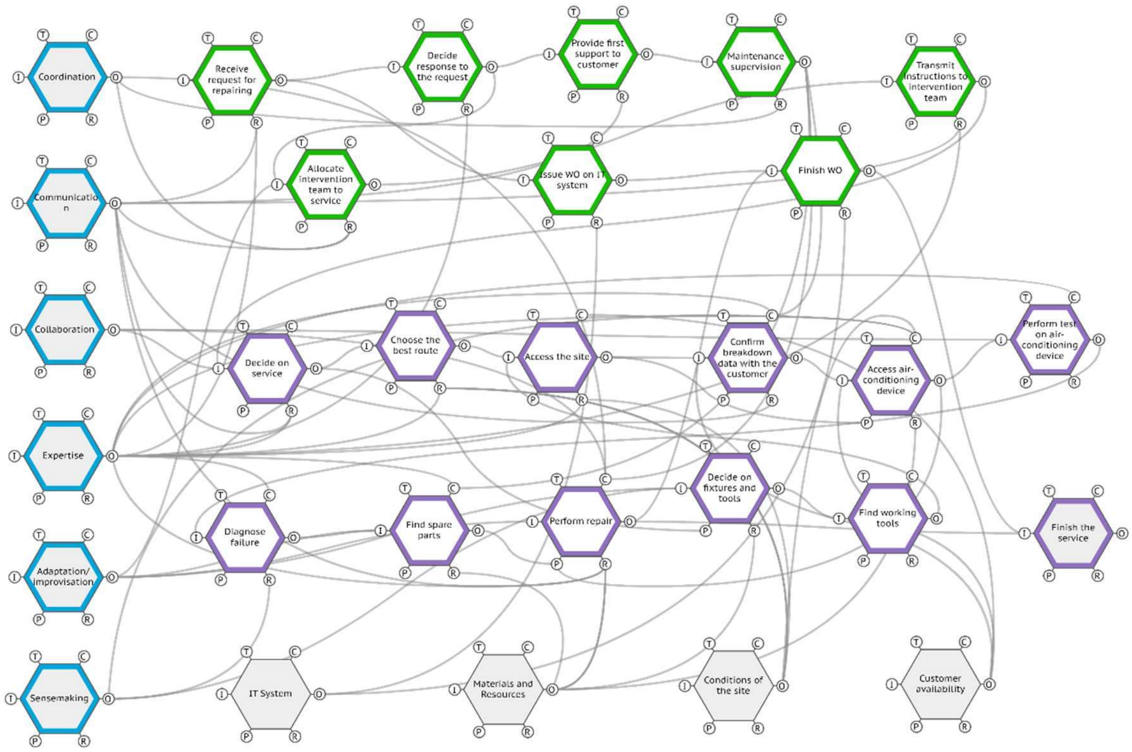

Figure 3 - FRAM instantiation to maintenance operations for sudden breakdowns in air-conditioning devices. This model is an offshoot of the general model developed by De Souza (2021)

Table 2 - Detailing macro-cognition for directly impacted functions by disturbances. Code for characterizing how a macro-cognitive function is connected to the FRAM function. R = resource; (I) = input; (C) = control

Function	Description	Potential disturbances	Macro-cognitive functions associated	
			Description	Resilience strategies
Receive request for repairing	The maintenance supervisor receives requests from the customer via phone or message	The customer provides unstructured information on the failure	Communication (R)	Eliciting additional data from the customer
			Expertise (R)	Using intuitive bias to interpret information from customer
Allocate intervention team to service	The maintenance supervisor allocates technicians to respond to the request	Specialized team unavailable	Coordination (R)	Providing the team with enough information that enables them to synchronize their efforts to achieve the goal
			Communication (R)	Establishing quick communication channels with technicians, e.g., via cell phone, or even in person
			Adaptation/ improvisation (I)	Providing a mixed team to respond to the request. It implies assigning other areas'

				staff to respond to the emergency
Maintenance supervision	The maintenance supervisor provides support to the team in the field	Multiple demands from the supervisor hinder the follow-up of the work	Coordination (R)	Empowering technicians to independently make decisions
Confirm breakdown data with the customer	Technicians need to cross-check with the information previously received	Inconsistencies of data provided by the customer	Communication (R)	Identifying inconsistencies from the initial description and making face-to-face elicitation
			Expertise (C)	Extending and adapting interpretations from prior experience
Access air-conditioning	Technicians access the air-conditioning device	Limited access conditions	Sensemaking (C)	Making observations and judgments on physical structures and sites
			Expertise (C)	Recognizing the situation and identifying an appropriate response
Diagnose failure	Technicians define the root cause of the failure to propose a repair	Novice or non-specialist worker assigned to the service	Expertise (C)	Taking advantage of intuition and patterns they have acquired to make an effective and plausible diagnosis
			Sensemaking (R)	Understanding critical factors and cues that might suggest a solution
Find spare parts	Technicians look for usable parts to perform repair	Unavailability of spare parts	Expertise (C)	Recording current actions to support decision-making or anticipate similar events in the future
			Adaptation/ improvisation (I)	Removing usable parts from out-of-service devices
Perform repair	Technicians engage in repairing the air-conditioning device	• Equipment limitations • Specialized team unavailable	Coordination (C)	Getting help from customers to find additional tools and equipment to perform repair
			Collaboration (C)	Sharing tasks between team members
			Expertise (R)	Recording corrective actions to support memory recall at future services

	Adaptation/ improvisation (I)	Adapting tools and equipment, and improvising procedures to solve the failure

4.3 Analyzing macro-cognition on the FRAM model (step 3)

4.2.1 Expertise

Typically, maintenance is requested via the Information Technology (IT) system. The maintenance supervisor analyses the request, issues a work order (WO), and then allocates the maintenance team to respond to the WO. However, in abnormal situations, occupants usually request maintenance either by using the phone or via a messaging app. Normally, the maintenance supervisor can provide first support measures, which consist of suggesting tests and preliminary checks on the air-conditioning device before the team's arrival.

Fig. 4 details the function "expertise" coupling with other twelve functions. The function "decide response to the request" encompasses decision-making regarding the criticality of the event. Our analysis indicated that requests are generally underspecified and ambiguous by the occupants. However, the maintenance supervisor takes advantage of its expertise to interpret data even partially provided., i.e., even an abstract description of the problem can be enough to generate assumptions about the work scope, and then transmits instructions to technicians.

Expertise primarily consists of tacit knowledge, rather than explicit knowledge (Klein, 2015), and it comprises mental models, perceptual skills, a sense of typicality, routines, and declarative knowledge (Klein and Militello, 2004). For example, in the function "diagnose failure" technicians aim to detect causes for the trouble reported. Detecting a problem is usually based on heuristics, which consists of mental shortcuts that enable workers to make decisions quickly and with minimal mental effort. On the other hand, during inspections, technicians are exposed to a wide variety of troubles in air-conditioning devices, which contributes to enrich their repertoire of failure modes in such devices, as well as how to fix them. This repertoire constitutes a rich mental model of how things function which contributes to better diagnosis and anticipation. However, novice technicians may not consider all potential causes for the failure.

For example, the case of inefficient cooling of air-conditioning devices could be caused by a variety of reasons ranging from dirty filters to leakage of refrigerant fluid. In this case, a novice technician may fail to diagnose the true cause of the failure. However, experienced technicians take advantage of their lived experiences since they can question their analysis to ensure they are addressing all possible failure modes. At this point, Crandall et al. (2006) point out that people with a high level of capability can apply previous experience to a wide range of tasks encountered in everyday activities, including choosing best practices for ideal performance and making judgments and discriminations in nonroutine cases. Moreover, technicians also stated that a set of best practices resulting from past experiences constituted a knowledge base for anticipating actions and resource preparedness to respond to similar events in the future. From their viewpoint, they can predict which types of service will be prolonged and what types of resources (e.g., ladder, scaffolding, etc.) will be needed based on their knowledge regarding the location of the device, as pointed out by one technician: *"depending on the type of equipment and the location, we already know everything that will be necessary to carry out the service".*

In accessing air-conditioning devices, technicians often deal with disturbances associated with, for instance, units that are surrounded by vegetation hampering the access to the device, structures deteriorated by natural occurrences like rain, units installed in confined spaces, and hindrances in the pathway hampering the access (de Souza et al., 2021). Maneuvering actions, in this case, benefit from expertise and sensemaking to adequately overcome those constraints.

Resilient performance in this context is about the training of the maintenance team to increase the capacity of response, and therefore, the effectiveness of the potential for anticipating. Prior exposure to feasible real-world scenarios can develop decision-making and team-management skills, which will make real-world challenges easier to tackle (Steen and Pollock, 2022). Thus, there is an opportunity to strengthen the sharing of all relevant experiences among people involved in the process.

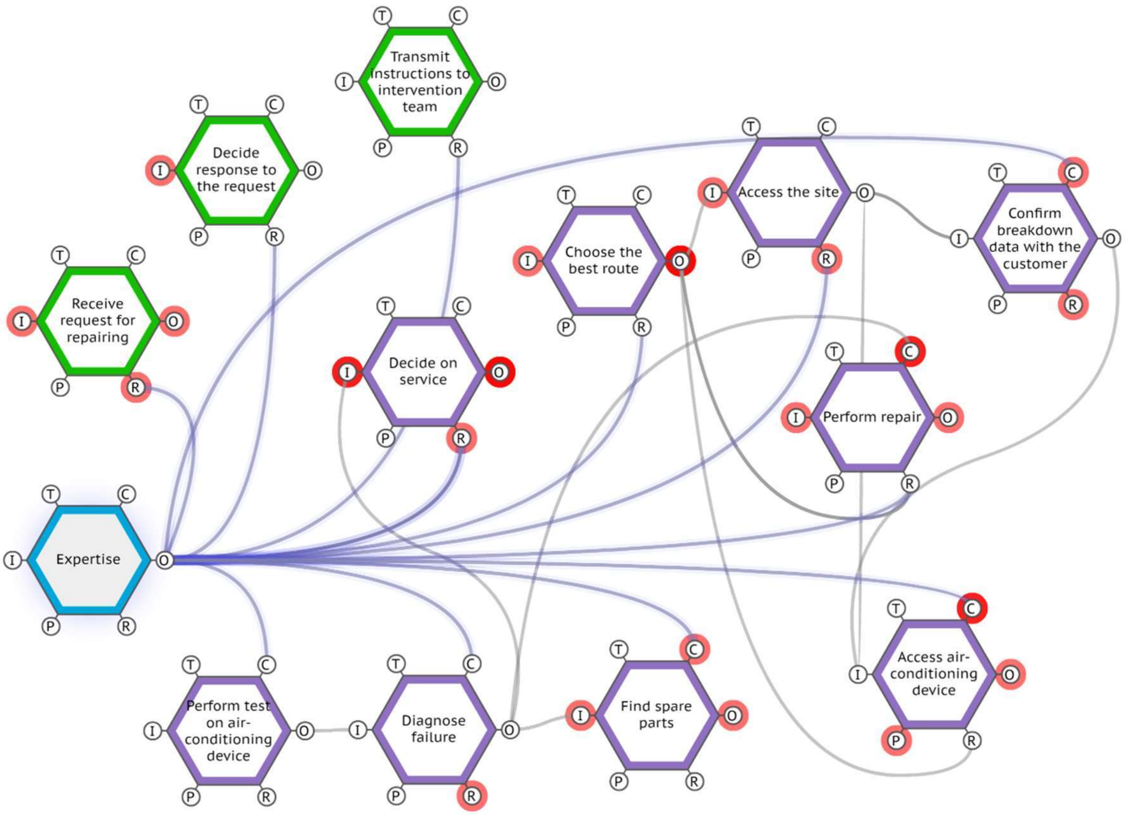

Figure 4 – Excerpt of the FRAM instantiation for inter-relationship of the expertise. Red circles around functions' aspects document connections with other functions of the model.

4.2.2 Sensemaking

As detailed in Figure 5, sensemaking controls the function "access air-conditioning device". At this moment, technicians can identify a clear frame of the safety conditions for accessing the air-conditioning device. Reports from workers reveal that there is a meaningful number of buildings with air-conditioning devices installed at height or underground, and the absence of conservation in such sites may contribute to accidents involving the maintenance team. Therefore, assessing such risk factors is a crucial task in detecting activities that could lead to falls, injuries, or even other accidents. The technicians' sensemaking is developed by using mental models (or schemas) (Klein et al., 2007) of contextual elements such as the position of the air-conditioning, fixing structures, conditions of access, etc., which support responding actions. On this subject, responding actions include a short meeting to decide on the intervention, as evidenced in the comment: *Upon arrival at the site, we assess the safety conditions. If is risky to work, we notify the person responsible for the property and abort the service.*

From the opinions of technicians, understanding the current context improves their capacity to deal with urgent demands, assess risks, and allocate needed resources for the service. Here, making sense of current conditions comprises the gathering of information, and assessing how the information maps onto potential scenarios or explanations (Patterson and Hoffman, 2012), which denotes the interplay of interpretations and actions (Weick et al., 2005). This process depends on responsibilities, procedures, and the experience and the training of the workers, e.g., in the use of technology (Kilskar et al., 2019), which constitute important strategies for adaptive behavior, which in turn is a prerequisite for resilience (Kilskar et al., 2018).

In the same way, as observed in this study on building maintenance, the importance of sensemaking in monitoring boundary conditions is very similar to sensemaking behaviors found in other recent applications, e.g., (Agnisarman et al., 2022; Steen and Pollock, 2022; Sushereba et al., 2021). The results have demonstrated that the sensemaking process of sharp-end workers is complex due to a variety of factors ranging from the experience and expertise level of the workers to the environmental conditions. Such complexity requires the workers to develop sensemaking skills for anomalous situations in which they are not able to recognize the situation immediately (Suss and Ward, 2018).

These studies agree that scenario-based training can contribute to effectively improving overall sensemaking skills, especially with the adoption of digital technologies to simulate real-world conditions, e.g., mixed reality (MR) (Agnisarman et al., 2022). These tools allow for the rapid presentation of a variety of cases without the need for physical apparatus (Sushereba et al., 2021). Thus, it could be an excellent training tool for the development of sensemaking abilities in activities for building maintenance.

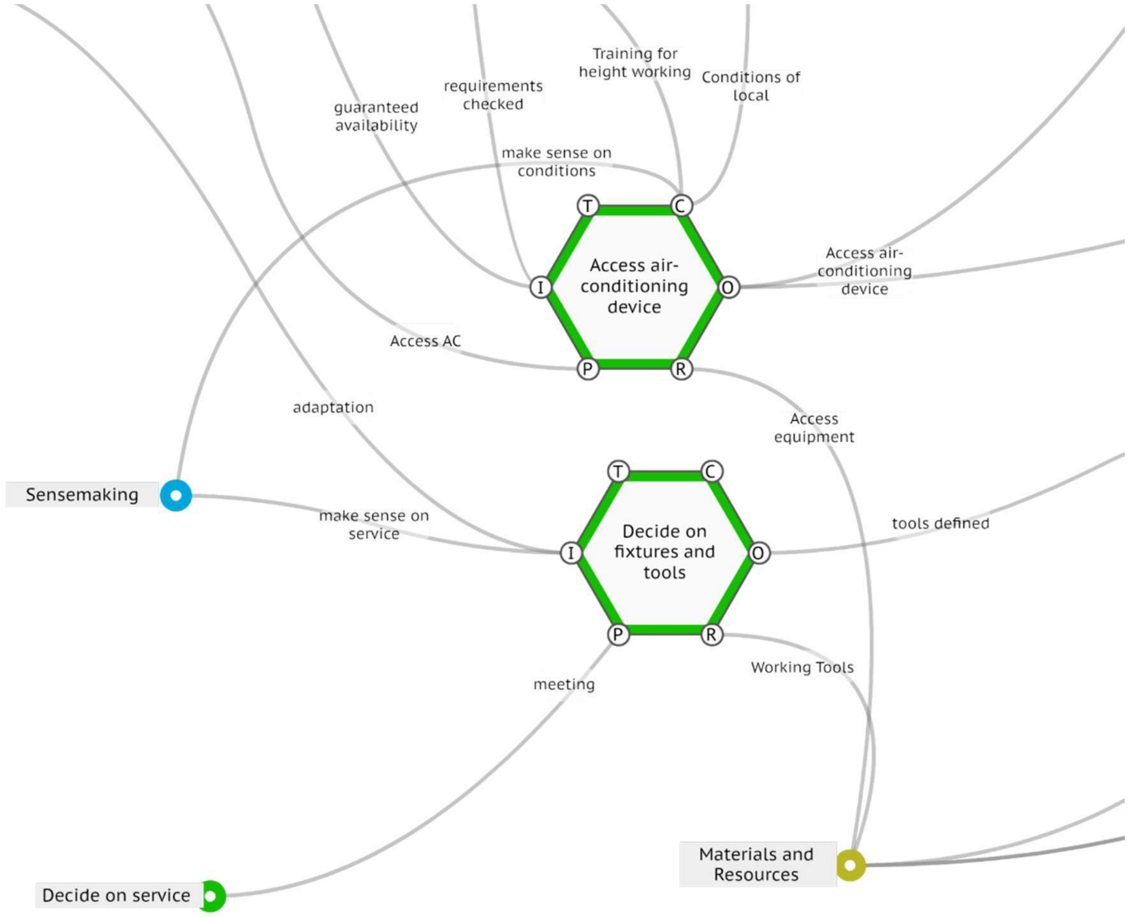

Figure 5 – Excerpt of the FRAM instantiation for inter-relationship of the sensemaking

4.2.3 Adaptation/improvisation

Fig. 6 details the function "adaptation/improvisation" coupling with four relevant functions: "allocate intervention team to service"; "find spare parts"; "perform repair"; and "decide on fixtures and tools". For example, the function "perform repair" constitutes a complicated task, since the work system is affected by many variables, from equipment limitations (ladder, scaffolding, and special tools) to availability of complete maintenance teams. On failures such as cooling deficiency, the maintenance team can usually provide corrective measures by performing cleaning to remove debris and contaminants or even adding refrigerant fluid into the unit. Conversely, performing a repair may involve replacing parts, and typically the customer is responsible for providing such parts. However, our analysis found this setting makes the process unsuitable for coping with urgent situations since the purchase process can be bureaucratic and time-consuming. It means that with the unavailability of spare parts, the repair may not be performed on time. Thus, to cope with the absence of spare parts technicians engage in adaptations or even improvisations, i.e., they usually maintain a set of serviceable parts in the workshop, which is represented by the function "find spare parts". Otherwise, the technicians seek out-of-service devices in attempting to remove usable parts to make repair possible. However, for critical cases that involve the replacement of the compressor, for example, the maintenance team does not have the means to handle such a situation.

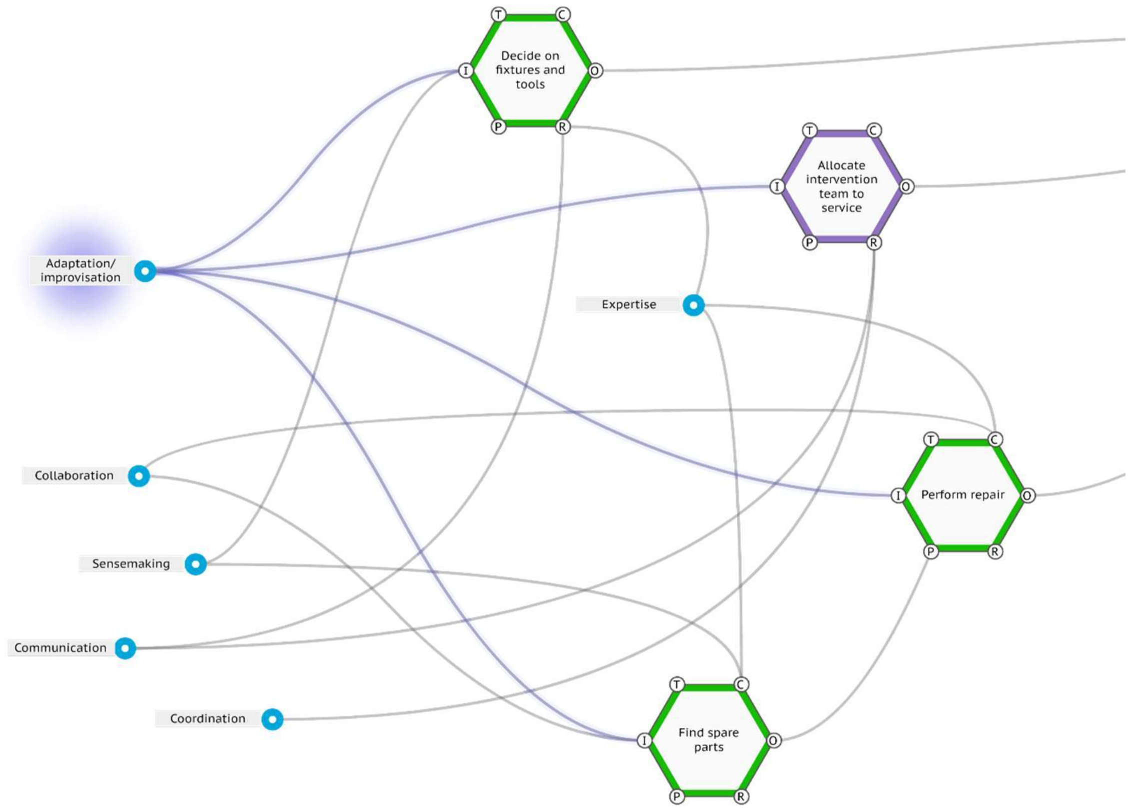

Figure 6 – Excerpt of the FRAM instantiation for inter-relationship of the adaptation/improvisation

Although adaptation and improvisation are terms often used interchangeably (Righi et al., 2015), nuanced differences are noted. Adaptation is close to general changes in the system regarding the allocation of resources whereas improvisation encompasses a quick and innovative adaptation in the response phase (Son et al., 2020a; Vera and Crossan, 2005). Therefore, from the viewpoint of the maintenance supervisor, improvisation is vital to allow immediate response in unexpected situations (e.g., sudden breaking down of devices), which requires a certain degree of flexibility in ongoing processes. This can be noted in the following account: *"Responding within a reasonable time window entails the need to perform attendance without the IT system; instead, the customer calls for maintenance by phone"*. According to one technician, this action is necessary to ensure that some high-priority situations are attended to on time. It involves the ability to allocate necessary tools, materials, and people, besides deriving *ad hoc* solutions to resolve such situations (Hollnagel, 2011). For instance, technicians are typically assigned to perform work by considering criteria such as the qualification of each one, (e.g., training for working at height), and workforce management (Souza et al., 2021). From this, the technicians are deployed to perform maintenance activities at one or multiple sites, and they do not work in fixed teams throughout the shift. During emergencies, the maintenance supervisor may reallocate technicians to specific services in the short term, depending on the necessity. Data analysis shows that strategies for responding manifest themselves mainly in the incorporation of adaptation actions into prescribed work. An adaptation phase occurs when a system is unable to absorb all external disruptions (Pawar et al., 2022). To enable adaptive responses to current conditions, flexible capacities, and resources should be maintained to compensate for additional foreseen and unforeseen demands (Provan et al., 2020). However, the supervisor pointed out: *"We deal with the scarcity of technicians with different specialties, which is crucial to attend to services that require a combination of technicians with different skills".* In their viewpoint, this indicates a chronic constraint in terms of immediate response to urgent calls. Therefore, this situation claims the adoption of anticipating actions to avoid undesirable results in the frontline.

A crucial part of improvisation comprises the individual's cognitive ability to extract cues from the environment, and to adopt certain strategies for specific times and situations (Cantelmi et al., 2022). Such actions are often adopted in the frontline to respond to emergency demands (Lundberg and Rankin, 2014) since sharp-end workers are better positioned to understand adverse situations, apply new insights, and appropriately respond from available resources (Phillips et al., 2022). Therefore, improvisation capacities may contribute to an organization's timely response to disturbances since individuals are led to think outside the box and use their discretion in dealing with severe disruptions (Stowers et al., 2020). In our study, such strategies comprise actions that are not provided by instructions or procedures but instead consist of improvisations that are implemented informally by technicians in the field.

4.2.4 Coordination

Fig. 7 illustrates the inter-relationship of the coordination and the collaboration with other five functions. In terms of coordination, for instance, the function "allocate intervention team to service" concerns finding available technicians to respond to the maintenance request. Our analysis indicated that the large number of WOs during the high-demand period causes delays in responding to requests. This is due to the limited resources and only three technicians available for HVAC systems. As previously illustrated in Fig. 3, when faced with such limitations, this function is also triggered by the macro-cognitive function "adaptation/improvisation". Hence, in an attempt to minimize the impacts of limitations, the maintenance supervisor coordinates with other crews to allocate even workers from other disciplines, e.g., electrical, to cooperate with the specialized technician allocated to the service.

At the same time, technicians argue that effective coordination is crucial because team members perform multiple interconnected activities, which requires that information flows freely intra-organizationally (among agents) and with external agents (e.g., occupants and regulators), as well as in a decentralized way. This means that new coordination clusters are created spontaneously from the empowerment of technicians for immediate decision-making when facing disturbances, which can be noted in the function "perform repair". This function exhibits the role of coordination among technicians: ongoing adjustments on the tasks are made to deal with the risk of accidents or unexpected occurrences, e.g., failures not previously detected. The coordination stands out in allowing teams to attend to intra-team goals while ensuring their actions are cohesive with organizational goals (Brown et al., 2021). Likewise, we noted this exemplar highlights the importance of coordination as underpinning effective customer attendance, as well as analyzing the extent to which operations remain safe.

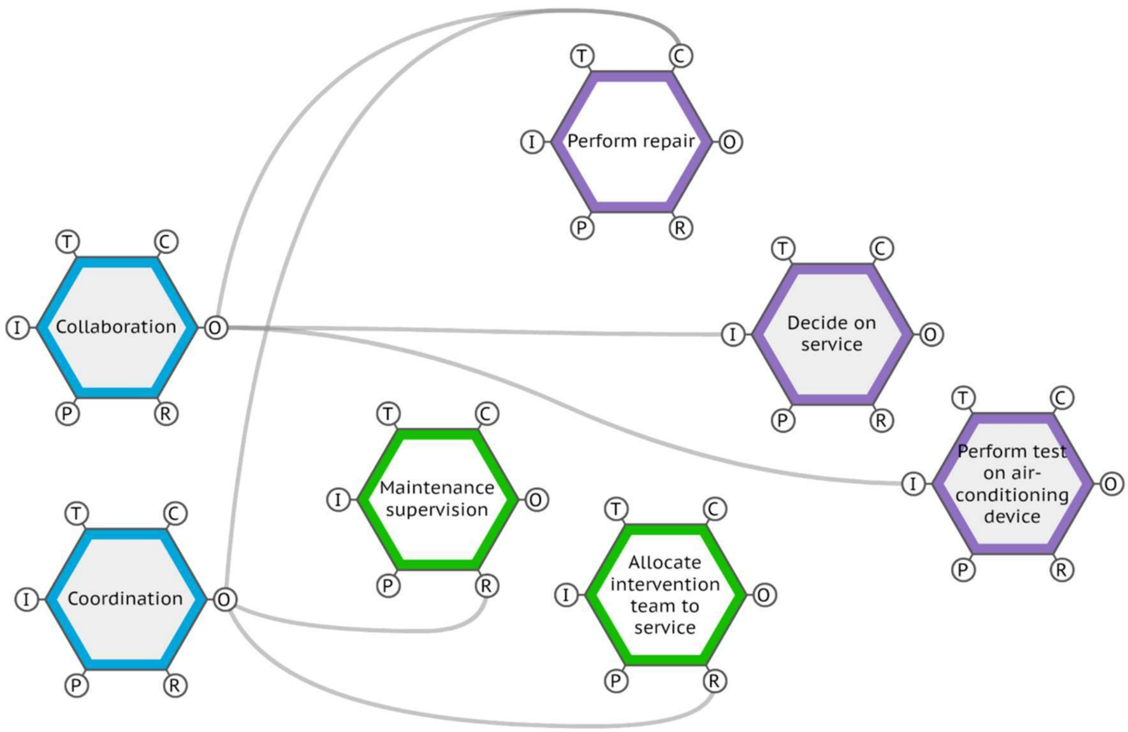

Figure 7 – Excerpt of the FRAM instantiation for inter-relationship of the coordination and collaboration

4.2.5 Collaboration

In terms of anticipating threats, collaboration across technicians is critical for the successful management of maintenance. Collaborative decision-making may positively influence subsequent tasks in terms of anticipating potential bottlenecks in the process, such as the noted in the function "decide on service", as previously detailed in Fig. 7. This function requires several decisions made collaboratively between team members concerning strategies to be adopted to accomplish the service (e.g., arranging special fixtures and tools needed for a particular service). One technician pointed out the importance of look-ahead planning to anticipate potential disturbances in the work course: *"This meeting we have is fundamental to plan all actions in order to be prepared before execution"*. Similarly, collaboration among technicians was also found to be a contributing factor to responding to unexpected situations in the function "perform repair". Concerning this, they said to share all relevant information about failure diagnosis and detect potential disturbances early as well as their future unfolds. These findings make collaborating activities crucial elements to anticipating and to responding problems and thus ensuring successful results. The frontline workers usually deal with ambiguous data regarding the service and a finite set of resources. Such conditions require the workers to creatively generate *ad hoc* solutions to satisfy constraints.

4.2.6 Communication

Communication also plays an important role in responding to events, mainly in emergencies (e.g., sudden breaking down of devices), which require the maintenance team to operate in time-pressured, and dynamic environments. Such conditions usually require actions not provided in standard procedures, including managing individuals, and teams, trade-offs of goals, and dealing with uncertainties (Steen et al., 2022). For example, the maintenance supervisor uses messages on *WhatsApp*™ to guide the field team on the failure, which is represented by the function "transmit instructions to intervention team", as can be noted in Fig. 8. During this process, the maintenance supervisor maintains intense communication with technicians to understand the impact of the failure on the building operation. However, this process is hindered due to misunderstandings in messages due to the poor mobile phone coverage in the region. In turn, in facing this disturbance technicians usually contact the occupant (customer) to take additional details on the service, which is essential for cross-checking information provided by the maintenance supervisor.

Similarly, in the function “perform repair”, the intense verbal interaction among team members allows for anticipating hazard situations and mitigating emerging risks during interventions on air-conditioning devices. In the view of technicians, effective communication between the involved people is necessary to ensure an efficient operation. On the other hand, ambiguities or misunderstandings will deteriorate the process. Therefore, as the capacity for coordination depends on effective communication (Comfort, 2007), providing workers with accurate, timely, balanced, and unequivocal information contributes to a more resilient performance during a crisis (Kim, 2021). Thus, suggested interventions by the workers to strengthen this factor included the enhancement of communication channels between the customer and the maintenance team, and among team members. This implies, for instance, re-designing the IT system because relaying accurate information is essential to establishing and maintaining a shared understanding of the present situation. In addition, the acquisition of radio communication equipment enables the maintenance team to coordinate their activities and act appropriately. Although the radio communication channel seems to play an important role in maintaining contact between geographically distributed team members, Takacs and Juhasz (2022) reinforce the lateral (face-to-face) communication channel plays an equally important and complementary role during the execution of tasks. Thus, a reliable communication process requires training of the team to improve interpersonal communication abilities (Tiferes and Bisantz, 2018), ensuring the information flows in an open, honest, accurate, and precise way (Roberts et al., 2019), which can greatly impact the effectiveness of overall team performance.

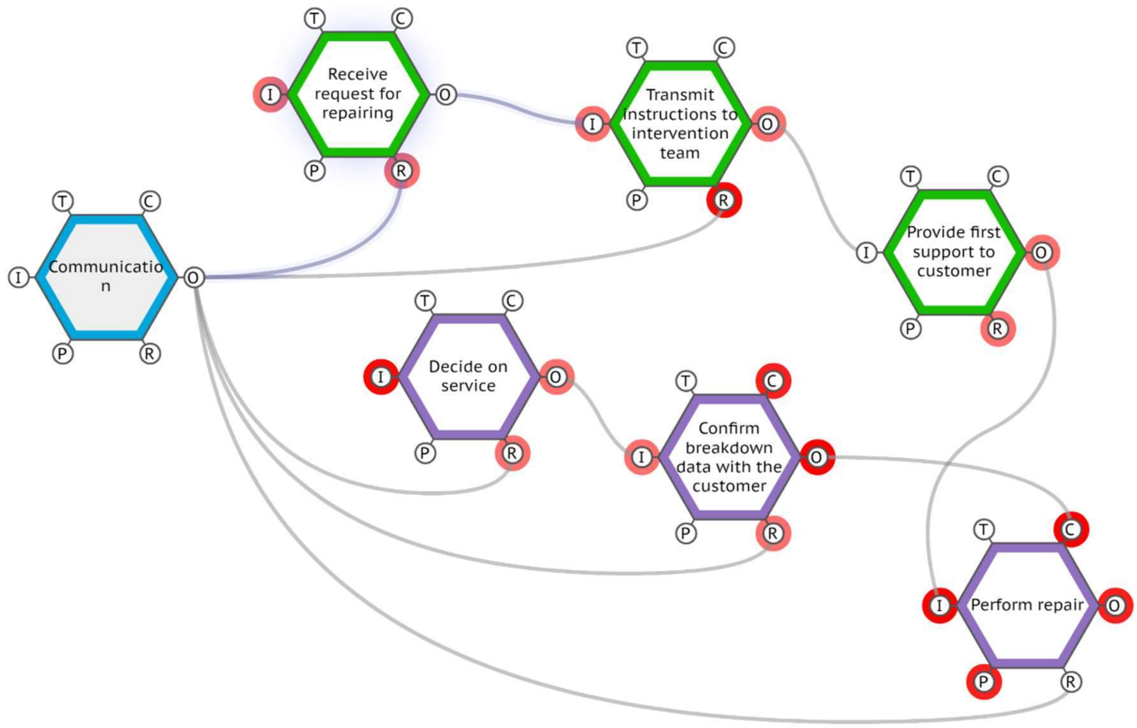

Figure 8 – Excerpt of the FRAM instantiation for inter-relationship of the communication. Red circles around functions' aspects document connections with other functions of the model.

5. Study limitations and future research directions

This study has some limitations which point to future research directions. First, this study has addressed only six macro-cognitive functions, and others unexplored in the current study might be examined to understand their impact on decision-making and their role in the overall resilience of the system. Second, building maintenance comprises a set of other relevant activities. This study, however, has focused on the maintenance processes of air-conditioning devices. A further investigation addressing other activities (e.g., electricity services, fire brigade, etc.) constitutes a promising research topic. Third, the current study suggests training processes as an option to refine the macro-cognition in maintenance teams, aiming to improve resilience abilities. Nevertheless, future studies should investigate the extent collective or individual training contributes to enhancing team resilience. Moreover, the use of digital technologies in such training should be considered a modern tool to support macro-cognitive processes, and likewise enhance the system resilience. Fourth, although in-depth information was obtained in the case study, the small sample size of participants limits the generalizability of the findings of this study to other building maintenance activities. Therefore, in order to expand the generalizability of the results, future studies are required to consider alternative modalities of maintenance and include more diversity and number of participants, including maintenance technicians and customers.

6. Conclusion

This study investigated how macro-cognition could contribute to the sharp-end operators' resilient performance. For this purpose, the FRAM was used to functionally map critical processes involved in maintenance operations during sudden breakdowns in air-conditioning devices for a large university campus in Brazil. Six macro-cognitive functions (sensemaking, expertise, adaptation/improvisation, communication, coordination, and collaboration) were examined for their impacts on responding and anticipating actions. The comprehensive FRAM model and the resulting analysis show that the expertise is the macro-cognitive function presenting more interactions. This evidence is due to idiosyncratic patterns of the domain, such as tasks are heavily based on common knowledge, and ever-changing scenarios in daily routines are difficult to predict. Thus, the analysis highlighted that the expertise function is crucial to provide a repertoire of adaptive behaviors to create resilient performance. Therefore, the training of the maintenance team on real-world cases, e.g., simulation-based training, could be a helpful way to increase the capacity of response, and also the effectiveness of the potential for anticipating.

Likewise, results from fieldwork show that functions related to teamwork (coordination, collaboration, and communication) are crucial to the quick response to sudden breakdowns. Such functions are often used in the frontline to respond to emergency demands. Although they have common attributes, the analysis shows that each one has specificities to be individually considered. For example, increasing the efficiency of communication channels between workers and occupants could greatly improve the team cognition process. The adaptation/improvisation function constitutes a fundamental ability to adequately respond to the multitude of scenarios in daily activities. The detailed analysis of maintenance activities shows that technicians have rich repertoires for dealing with unexpected situations, for instance, the lack of a special tool. Moreover, they present sophisticated mental models to solve problems in performing repair from cues extracted from the environment. On the other hand, the sensemaking function is useful for managing improvisations, preventing them from resonating in the system and leading to loss of control.

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Appendix 5

Information technologies in complex socio-technical systems based on functional variability: a case study on HVAC maintenance work orders

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Article

Information Technologies in Complex Socio-Technical Systems Based on Functional Variability: A Case Study on HVAC Maintenance Work Orders

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Abstract: Information technology (IT) systems are known to promote improvements in quality and productivity of the work environments of complex and adaptive socio-technical systems that span hardware, community and software aspects. Systems development lies in eliciting and specifying requirements. However, current requirements of elicitation techniques are limited to correctly understanding the complexity involved in socio-technical systems. Therefore, approaches based on Resilience Engineering can provide concepts and methods for a better understanding of socio-technical systems' functioning. This study aims to increase the application of the Functional Resonance Analysis Method (FRAM) in the requirements elicitation process. Specifically, understanding variability and its role in enhancing the requirements elicitation and specification process for the design/redesign of IT systems in complex socio-technical systems deployed in building maintenance is the main goal. This study proposes the merging of human factors and ergonomics (HFE) and Resilience Engineering concepts with Software Engineering. A case study was performed with workers to produce requirements specifications for work order issuing activity. This case study indicates the usefulness of the proposed approach for the specification of functional requirements to redesign the IT system examined. FRAM enables inferences to be made from hidden or fuzzy situations that are often not expressed by system users or are not detected by the system designer.

Keywords: information technology systems; socio-technical systems; requirements elicitation; FRAM; building maintenance

1. Introduction

Complex socio-technical systems [1] involve a multifaceted interaction between humans, machines, and the environmental aspects of the work system [2]; this can comprise some subsystems and subtasks linked in known or unknown ways [3]. A complex system is composed of a system for which it is difficult, if not impossible, to reduce the number of parameters or characterizing variables without losing its essential functional properties [4]. The entire system may be affected by small oscillations occurring in specific tasks, leading to potentially critical consequences [5]. Such systems are known for being prone to unexpected variability, which means that actors will vary their actions in response to situational demands or disturbances to achieve a system's goal. The functional variability tends to propagate quickly and non-linearly due to tightly coupled processes [6,7].

In socio-technical systems, human, organizational, and software agents rely heavily on each other to fulfill their respective objectives [8]. Information technology (IT) systems can promote the improvement of quality and productivity in the work environment of complex socio-technical systems. Modern developments in IT systems related to the building maintenance activities have been implemented to facilitate maintenance management, including failure analysis, documentation of maintenance, fault location, repair, and reconstruction [9]. For example, in non-residential infrastructures, it would be impracticable to manage adequately the maintenance of heating, ventilation, and air conditioning (HVAC) systems without an IT system. Therefore, there is a need for effective evaluations of IT to ensure that the system requirements meet the needs of users. In this domain, the peculiarities of each organization and the complexity involved in the activity stand out as obstacles for embedding those technologies. In addition, for the adoption of technological devices to support complex activities, understanding how work is done becomes a difficult task because of the interdependence among a large number of variables [10].

Requirements elicitation plays an important role in the information technology design, since it has a cascading effect on subsequent processes; defects introduced at the requirements engineering stage have a negative impact that is significantly higher than defects in the later development stages [11]. An inadequate requirements specification acts as a catalyst to other problems, such as low team productivity and difficulty in maintaining software [12]. Moreover, unclearly describing the requirement specifications may become difficult to develop high-quality software [13]. In addition, it is significantly cheaper to elicit and specify requirements during the requirements engineering stage than during later software development activities [14].

Requirements elicitation aims to identify the requirements of IT systems according to the need of the customers and users, which is not always straightforward [15,16]. For many complex domains, users usually do not have a complete understanding of the problem domain, including the difficulty of describing their needs and expectations to the designer in a systematic way [17,18]. This situation increases the tendency to obtain incomplete and ambiguous data. Therefore, this stage is recognized as the most difficult, error-prone, activities during the software engineering life cycle [19], since requirements engineers are usually not trained to elicit this kind of information [20].

Moreover, current elicitation techniques are limited to gain requirements in socio-technical systems; these are either critically dependent on the selection of experts to ensure the successful elicitation of requirements, which require the wide expertise of analysts with formal methods and techniques, or lack a proper methodological approach to deal with these requirements [8]. Furthermore, typical approaches to elicit software requirements are not always sufficient to correctly understand the complexity of IT devices or to anticipate likely error situations [21]. Hence, they are not well suited for eliciting deeper social and features of socio-technical systems [8], since those are subject to variability (non-linear characteristics), including the inherent complexity. Depending on how requirements are elicited, analysts may not be able to predict variations that emerge when the system is functioning [21]. This situation is often perceived as a major obstacle for knowledge eliciting, which could lead to unclear and incomplete requirements documents [22]. As a result, those systems might become underutilized, which can cause management difficulties and consequently the loss of quality in the system utilization.

Researchers and practitioners in IT systems have long recognized that understanding the business processes that an information system must support is crucial to eliciting the needs of its users [23]. Among the various methods developed for business modeling, it is worthwhile to mention the Structured Analysis and Design Technique (SADT), a functional language [24], which is standardized into the modeling language Integration Definition for Function Modeling (IDEF0) [25]. This technique provides a means for modeling activities, actions, processes, and operations required by a system or enterprise as well as the functional relationships in a structured way [26,27]. However, it excludes an in-depth description when gathering contextual and requirements information [28]. Moreover, IDEF0 presents some drawbacks that affect its suitability for eliciting requirements in complex socio-technical systems once the method provides a static representation of the system, indicating linear functional relationships that conflict with the characteristics of complex socio-technical systems. IDEF0 is more focused on the description of the tasks and their orders than how the tasks are performed [29]. Therefore, approaches providing a depth analysis focusing on human behavior during the task execution and its inherent variability are the most suitable.

To improve requirement elicitation and specification in situations with a high-cognitive workload, Software Engineering can benefit by using practices of human factors and ergonomics (HFE). These practices bring techniques to enhance the understanding of how people work by providing services and tools that can be used to design an IT system [30]. HFE research provides insights and tools that could help developers design IT systems that reliably match "Work-as-Done" (WAD), instead of "Work-as-Imagined". These approaches have been adopted to facilitate and equip stakeholders involved in the design process with the knowledge necessary to the coupling between traditional engineering and HFE disciplines [31]. Some examples of recent studies, examining the role of HFE in software engineering can be mentioned. Jatobá et al. [10,30] examined the role of cognitive engineering to support the improvement of software requirements specifications, used in the healthcare domain. In addition, Dey et al. [18] proposed a methodology based on repertory grids to help users express their expectation of the IT systems in a socio-technical environment.

Resilience Engineering [32] emerges as a concept that could be understood as managing the preparedness of the organization to respond to unexpected events [33]. These concepts can be applied to produce tools to understand how people work and to proactively manage risk, acknowledging the inherent complexity of system functioning and the need for performance variability [34]. Functional Resonance Analysis Method (FRAM) [21] is a resilience-based tool that emphasizes the investigation of functional aspects, which is a key for modeling dynamic interactions, and performance variability, rather than physical aspects [22]. Moreover, it enables in principle the modeling of any interaction type (e.g., social interactions, the flow of materials, logical dependence) [23], which provides a broader source of information when compared with classic representations of business processes such as the Business Process Management and Notation (BPMN) model [21]. A FRAM model shows the non-linear coupling between functions and their inherent complexity. It illustrates how the variability spreads along with the system, which can lead to positive as well as negative results. Recently, De Carvalho et al. [21] conducted an experimental study comparing the BPMN and FRAM in an attempt to deal with the elicitation and specification of IT requirements in complex socio-technical systems, specifically in the healthcare domain. As such, it seems that FRAM is an adequate methodology to address the activity complexity, thereby contributing to the most reliable elicitation and specification of requirements for IT systems.

Regardless of the advances obtained by including the FRAM in the requirements elicitation process, empirical studies on the specific contributions of Resilience Engineering in the design or redesign process of IT systems are still scarce [35]. Therefore, an approach that integrates Software Engineering, HFE, and Resilience Engineering practices is timely. Given this context, this study aims to increase the application of FRAM in the requirements elicitation process of socio-technical systems. More specifically, the purpose of this study is to find out how variability understanding contributes to the requirements elicitation and specification for the design and redesign of IT systems to support the work in complex socio-technical systems. An empirical case focused on the maintenance of heating, ventilation, and air conditioning (HVAC) systems, specifically in the issuance of work orders (WOs) was addressed by using the FRAM.

The remainder of the paper is organized as follows: Section 2 presents a basic concept on requirements elicitation and specification. Section 3 presents an overall approach to FRAM. Section 4 introduces the details of the proposed method, including the framework used to conduct this study. Section 5 illustrates a case study by using the FRAM to support the process of requirements elicitation and specification. Section 6 presents discussions about the results. Finally, the last section presents the conclusions with the research contributions and possible future directions of research.

2. Requirements Elicitation and Specification

Requirements engineering (RE) is a branch of Software Engineering dedicated to the process of requirements specification that software must solve. The system requirements express the description of what the system should do and the obstacles to its operation. RE should be focused on precisely defining the real problem that the software must solve by describing the requirements in terms of how the proposed software should affect the environment [36].

The RE processes usually include four high-level tasks. These processes focus on assessing if the system is useful to the business (feasibility study), discovering requirements (elicitation and analysis), translating these requirements into some standard form (specification), and checking if the requirements define the system that the customer wants (validation) [36].

After an initial feasibility analysis, the next stage of the requirements engineering process is requirements elicitation and analysis. In this stage, designers seek to discover from stakeholders what services the system should provide, the required performance of the system, and hardware constraints, among others [36]. It is noteworthy that a requirements elicitation process is not trivial. The process needs to handle both needs and requirements. Needs are the goals and wishes of the system from the customers' perspective, whereas requirements represent perceptions of the system based on the designer's interpretation [37]. A true elicitation must encompass all the aspects of the context that can affect the system or its use rather than only capturing the customers' needs [20].

System designers can utilize a set of elicitation techniques to gain relevant information to specify requirements. The applicability of each technique depends on the context in which the elicitation is used. Some traditional techniques include but are not limited to open interviews, structured interviews, ethnography, card sorting/laddering, questionnaires, protocol analysis, repertory grid, brainstorming, Delphi technique, prototyping, focus group, scenarios, and use cases, among others [16,38].

The main action to cope with the user's extracted requirements is to register them in a standardized way. This standardized documentation assists stakeholders with understanding and organizing data, avoiding the raw data, which in many cases do not contribute to support decisions at the system development stage. Thus, this document so-called software requirements specification (SRS), establishes the basis for a documented agreement between customers and designers. SRS reports what stakeholders expect from the software. It also allows rigorous requirements evaluation before the start of building the software. This step also provides a realistic basis for estimating costs, risks, and product timelines.

The IEEE 830 standard [39] standardizes the SRS process, providing a set of best practices for developing an acceptable document. This document contains the specifications, containing all the technical details, including the functional and non-functional requirements of the system to be developed. The SRS will describe the behavior of the system under various conditions as completely as necessary, as well as the desired system qualities, such as performance, safety, and usability. This study uses the SRS from the point of view of the IEEE 830, focusing on specifying the functional requirements to redesign the IT system used in the issuance of WOs for the maintenance of HVAC systems.

3. Functional Resonance Analysis Method (FRAM)

FRAM [3] is a systemic analysis method that is used to describe the activities of a complex socio-technical system. This method considers the non-linear nature of the system performance rather than build a sequential cause–effect model of events over time [40]. FRAM enables the analysis from past events of a complex system, such as an accident investigation, safety management, and complexity management up to possible future events as a risk assessment [41].

The main purpose of FRAM is to build a model of the functions of a system that describes how performance variability may occur in the work-as-done (WAD) and how the effects may spread through the system. Regarding the graphical appearance of a FRAM model, for professionals who have never seen it, it seems a complex structure, which it is not. Indeed, the outcome analysis is not an algorithmic process, but rather the representation of the non-linear relationship among users working together [42].

FRAM has been extensively applied to the understanding and identification of variability and resilience in complex systems in several domains, such as aviation [43–45], construction [46,47], manufacturing [48], environmental [49], healthcare [50,51], the oil industry [42,52,53], and the maritime industry [54]. Other FRAM's applications are found in extensive mappings, such as in [41,55]. This methodology is based on four principles [3]:

- Equivalence of successes and failures: Failures and successes occur in the same way, i.e., everyday work variability;
- Principle of approximate adjustments: Work-as-done (WAD) never completely correspond to work-as-imagined (WAI). Workers typically adjust their performance to suit existing conditions.
- Principle of emergence: The performance variability of a function is rarely large enough to serve as the only cause of an effect or even to constitute a malfunction. Acceptable and unacceptable results are emergent rather than resultant phenomena, as they cannot be explained just by a cause–effect relationship of the operation of specific components or parts.
- Functional resonance: This latter principle states that the variability of a function may combine with the variability from another function, which causes a functional resonance with a difficult prognosis and significant uncomfortable management. Where it has become a utility to the organizations, the identification of functional resonance phenomena is cited as an instrument to locate management demands, including specific actions. In this case, losses in maintenance quality, delay, or incorrect maintenance are some depictions of undesirable effects.

To build a FRAM model, it is necessary to follow four steps, established by Hollnagel [3]. The first step is the identification and description of the functions, which can be human, technological, or organizational, depending on the nature of the function in the system. This step seeks to describe how the work is done every day, highlighting how the functions interplay with each other, rather than to build an overall flowchart or a function's structure. FRAM and IDEF0 are similar in terms of decomposing the system functions by using the four aspects of input, output, control, and resources. FRAM extends the number of aspects to include preconditions and a specific aspect representing temporal constraints [29]. The graphic representation of a function is a hexagon, consisting of one output and five inputs. Each vertex of this hexagon is identified as one of the six aspects [3]:

- Input (I): what triggers the function or what is processed or transformed by the function;
- Output (O): what is the result of the function, it can be either a state change or a specific product;
- Precondition (P): mandatory conditions that must exist before the function can be performed;
- Resource (R): what the function needs or must consume when it is carried out to produce the result (the output);
- Control (C): what controls and monitors the function to match the desired output.
- Time (T): temporal requirements or constraints of the function, regarding both duration and time of execution.

In the graphical language of FRAM, multiple hexagons can be displayed together, and the functions are interconnected by a set of lines (or arcs) through single or multiple vertices (or corners). In the FRAM vocabulary, lines or arcs are referred to as couplings [56], which are interpreted as paths for the spreading of variability throughout the system, as it can become the basis for functional resonance [57]. As noted in Figure 1, a function i could be linked with another function j through vertices $v(I, O, P, R, C, T)$. Whilst the vertices $v(I, P, R, C, T)$ represent input aspects that characterize the functioning of the function i, the vertex O feeds a function j or dozens of other system functions from the result produced by the function i. The FRAM Model Visualizer software [58] has been developed to help build FRAM networks as well as track functions and their aspects [59].

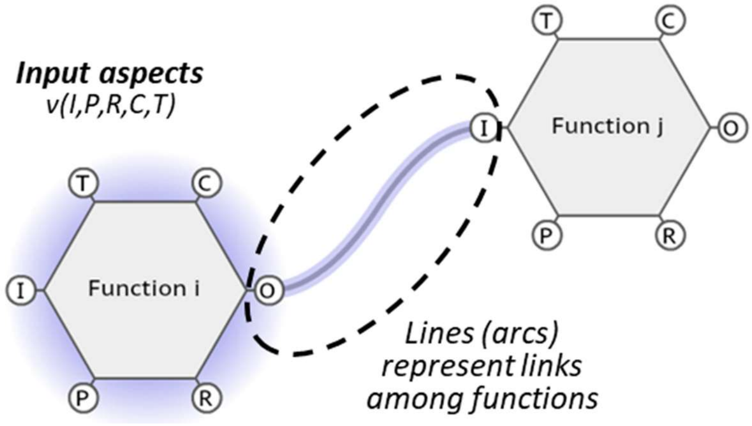

Figure 1. Example of the graphical language of Functional Resonance Analysis Method (FRAM) model.

The second step is the characterization of the output variability of each function that constitutes the FRAM model. Variability analysis is provided to identify the points that most interfere in the work system performance. To classify the time-related variability, this study uses the following terms: (i) "Too late" when the output of a function does not occur within the exact time specified; (ii) "On time" when the output occurs within the exact time; and (iii) "Too early" when it happens earlier than expected. To classify the variability concerning the precision, this study uses the following terms: (i) "Precise", for outputs that meet the needs of a subsequent function; (ii) "Acceptable", for outputs that depend on some degree of regulation; and (iii) "Imprecise", for incomplete or ambiguous outputs that request additional interpretation or conferencing.

The third step is to analyze how the potential variability of each function can become resonant in the entire system, leading to undesirable outcomes. Hollnagel [3] suggests that looking for functions with multiple couplings may be a first step in determining whether functional resonance can occur. If so, other actions must be taken to evaluate the likelihood and magnitude of variability and how it might affect other functions.

The fourth and last step in the application of FRAM is the monitoring and managing of the performance variability. In this sense, Hollnagel [3] proposes that the most efficient strategy is to adopt actions to damping negative effects, eliminating those that can lead to undesirable outcomes and, conversely, propose actions to enhance positive effects, without losing control of the activities.

4. Materials and Methods

This study proposes the merging of HFE and Resilience Engineering concepts to drive the elicitation and specification of requirements in Software Engineering. The approach proposed in this paper comprises three phases, which can be split into steps, as shown in Figure 2. The preliminary analysis comprises a single step called context description. The remainder phases, i.e., requirement elicitation and requirements specification, must be performed iteratively. Each phase is explained in the next subsections. This approach was used in a case study, as shown in Section 5.

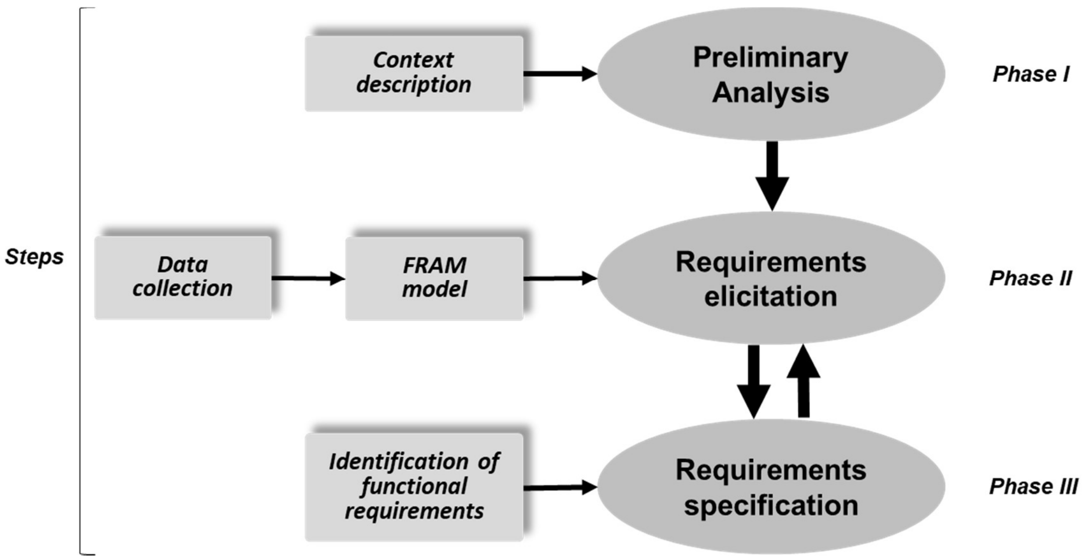

Figure 2. The proposed method's framework for requirements elicitation and specification using the FRAM model.

4.1. Phase I: Preliminary Analysis

The goal of this phase is to gain initial knowledge about the organization. This phase consists of the examination of the organizational strategy, vision, and objectives, core business process, identifying process flows, stakeholders involved, resources required, the organizational culture [60], and a broad spectrum of work situations, including the recognition of the physical structure. To perform this phase, the analyst should plan a script including some interviews, collecting documents, procedures, and tools that people use while performing their work. In addition, to constitute a broad understanding of the organization, the analyst should make a walkthrough, identifying agents and recording relevant work situations, aiming to establish synergy to the next phases.

4.2. Phase II: Requirements Elicitation

Requirements elicitation is considered an intensive, complex, and multi-disciplinary process. This task seeks to develop software systems for solving users' needs and satisfying stakeholders' objectives [8]. This phase aims to collect and analyze data from the empirical field that enable the construction of a representative model of the WAD with the support of FRAM. It is noteworthy that the analyst should focus on daily tasks to understand how the work is actually performed. In summation, this phase enables us to gather users' needs and recommendations that become requirements for redesigning the IT system. Strategies used for data collection and modeling of the WAD with FRAM are explained later in the next subsections.

4.2.1. Data Collection

Having as a basic premise the understanding of how the work is done, interview questions were designed and uses to collect data. The interviews were not structured by long questionnaires. The question to the workers and requestors boiled down to: "How do you perform your task?" In addition, a template containing the main topics was designed beforehand as a guide for the semi-structured interviews.

Ethnographic observations [61] were carried out to complement the data collected through interviews. This involved recording relevant details, schemes, and flowcharts to facilitate the understanding of WAD and subsequently support the construction of the FRAM model. A total of 17 visits were made in three months to the site of a Brazilian institution for research and development (R&D) located in the city of Rio de Janeiro. The data collection was achieved using four sources:

- Analysis of existing formal documentation: a documental analysis was undertaken to review the process mapping issued by the managers and policymakers. Although few processes were mapped, in this opportunity, five flowcharts in BPMN concerned with building maintenance were examined;
- Interviews with the maintenance supervisor: semi-structured interviews were held with the maintenance supervisor in three meetings to identify key aspects of maintenance management in the R&D organization to map the main processes;
- Interviews with requestors: semi-structured interviews with ten requestors were undertaken to understand how maintenance is requested, including the role of the current IT system used as a support tool for this specific task;
- Open-ended observations: these observations were used to record the behavior of people while they were performing their activities, aiming to complete data obtained from interviews. During the observations, informal conversations were held with participants to comment on the task being observed.

4.2.2. FRAM Model

In the first step of FRAM [3], the collected data enabled identifying the relevant functions and their couplings in everyday operations. These data were used to build a realistic FRAM model for the issuance of WOs.

In the second step, this study sought to understand the potential variability in the output function using data from experts on the subject and information captured by the analyst. Potential variability regarding timing and precision was disclosed to examine the socio-technical system's behavior and outcomes. Therefore, the influence of IT on issuing WOs was examined.

The third step sought to analyze how the variability may spread in the entire system, as well as the strategies used by agents to deal with these effects. Finally, the fourth step aimed to describe actions to mitigate the negative effects of variability and to amplify the positive effects, enhancing its occurrence. These actions aim to increase the system's resilience and improve the user interface, reducing the cognitive workload, and consequently minimizing quality losses in the issuance of WOs for the maintenance of HVAC systems. In addition, this step enabled the requirement elicitation to enhance the IT system.

This study used the software FMV® [58]—FRAM Model visualizer—to build the graphical representation of the functions and their couplings. The FRAM model contributed with relevant outcomes for specifying requirements in an organized way. The phase of requirements specification is disclosed in the next subsection.

4.3. Phase III: Requirements Specification

The requirements specification refers to detailing in a specific way all the requirements previously gathered as a result of the FRAM model. Representing needs into specifications means expressing precisely the elements of the technical solution to the design team [35].

Identification of Functional Requirements

This step shows how SRS can be strengthened by incorporating results from the approach proposed in this paper. As previously disclosed in Section 2, the IEEE 830 standard [39] standardizes the SRS process, providing a set of best practices for developing an SRS document. This study focused on specific requirements, as recommended in the IEEE 380 standard, as shown in Section 3. Furthermore, this study aimed to specify only the functional requirements to redesign the IT system. The specification of non-functional requirements may be addressed in a future study.

To evolve the traditional approach of requirement specification, this study proposes to add some elements in the frame of requirements recommended by the IEEE 830 standard. Thus, in this study, these elements are aggregated to each stated requirement to constitute a broad description of the user requirements, which is followed by a description of the system requirements in enough detail level to allow the system redesign. These elements consist of a concise title to the requirement, the agent responsible for triggering the requirement, the goal, the description of the requirement, and the outcome performed by the requirement.

5. Results

Fieldwork was undertaken in an R&D organization, especially in the department for building maintenance (DBM), which is responsible for managing the maintenance of the organization buildings. Particularly, this was done by looking at variability and discussing ways to redesign the IT system, highlighting the issues that would lead to positive outcomes while discouraging negative outcomes.

5.1. Phase I: Preliminary Analysis

This phase aims to show a broad vision about the operation of the building maintenance, the work organization, as well as a brief description of the way that workers regularly use to issue a WO. The next section presents the empirical field used in the case study and explains in detail the context involved in this study.

Context Description

The empirical field is a Brazilian institution for R&D located in the city of Rio de Janeiro. This institution is the largest engineering education and research center in Latin America, consisting of 13 graduate programs in engineering, 131 laboratories, 346 professors, and 457 employees. The DBM is a specialized sector in the organizational structure responsible for maintaining acceptable use conditions in the territories of the R&D organization. For this, the work carried out in the DBM comprises six groups: electrical, plumbing, HVAC, civil works, metal works, and carpentry/furniture. The DBM has never undergone any type of sizing to verify the number of workers needed to carry out the maintenance tasks. Currently, the department has twenty-six professionals, being one maintenance supervisor (one civil engineer), one assistant, and twenty-four technicians. Teams are multidisciplinary and perform maintenance in all the R&D territories.

The overall process of building maintenance comprises three great stages: maintenance request, request analysis, and maintenance execution. This study comprises a part of broader research in the building maintenance domain. Particularly, this article focuses on the stage of WOs issuance specifically in requesting for maintenance in HVAC systems. This stage embraces the maintenance requests and the analysis of them. The stage of the maintenance execution has been not included in this article, which may be disclosed in upcoming studies.

Broadly speaking, customers request maintenance using an IT system, namely CISI *(Centro de Integração de Serviços de Informática)*, which is a web-based platform that aims at computerizing requests for building maintenance at R&D territories. To perform the maintenance, the maintenance supervisor should analyze the customers' requests and issue a WO. The issuance of WOs is carried out in the maintenance management office. Two professionals work in the office: a maintenance supervisor and one assistant. The maintenance supervisor is responsible for allocating the technical team, analyzing, issuing, closing, and filling WOs. It is noteworthy that, also, in these activities, the maintenance supervisor needs to escort the technicians in some maintenance tasks closely. The assistant is responsible for issuing WOs, controlling tools, controlling staff, and answering calls. Eventually, one electrician helps in the office in the absence of the other two employees.

The process manager made available the existing flowchart illustrating the process of issuance of a WO. Figure 3 illustrates the process of issuance of a WO, as designed by the process manager. To trigger a request, the user fills the fields contained in the CISI screen. The screen shows three fields to fill, as follows:

- Cost center: This is the administrative unit to which the requestor is attached;
- Place: This is the laboratory or classroom where the maintenance is located;

- Description of the service: This is the field destined to the user so that it describes, with his words, the required maintenance.

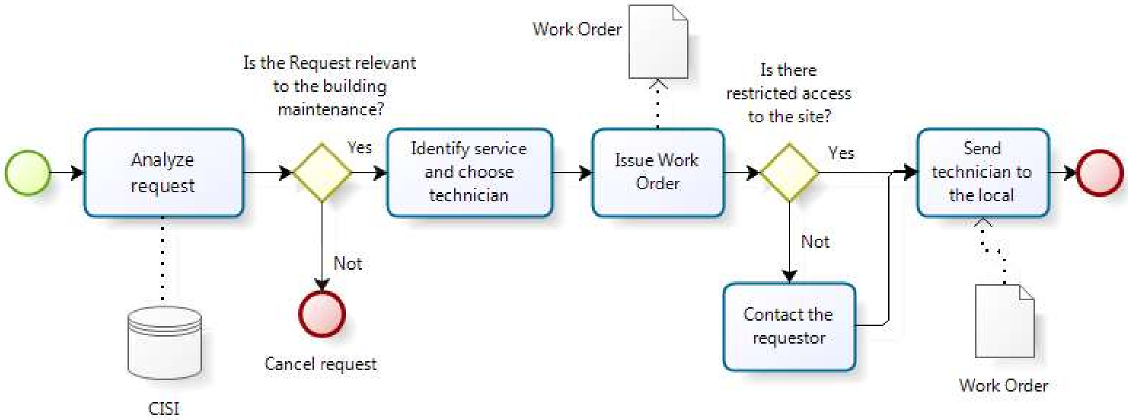

Figure 3. Example of the existing Business Process Management and Notation (BPMN) diagram representing the overall process of work order issuance for the building maintenance.

In complex socio-technical systems, the WAD is always different from WAI by those who write guidelines and procedures [62,63]. Therefore, the researcher aimed to understand how the tasks are performed realistically. For this purpose, based on interviews and observations, the researcher engaged in producing an equivalent flowchart representing the WAD. Figure 4 shows the WOs issuance process in BPMN.

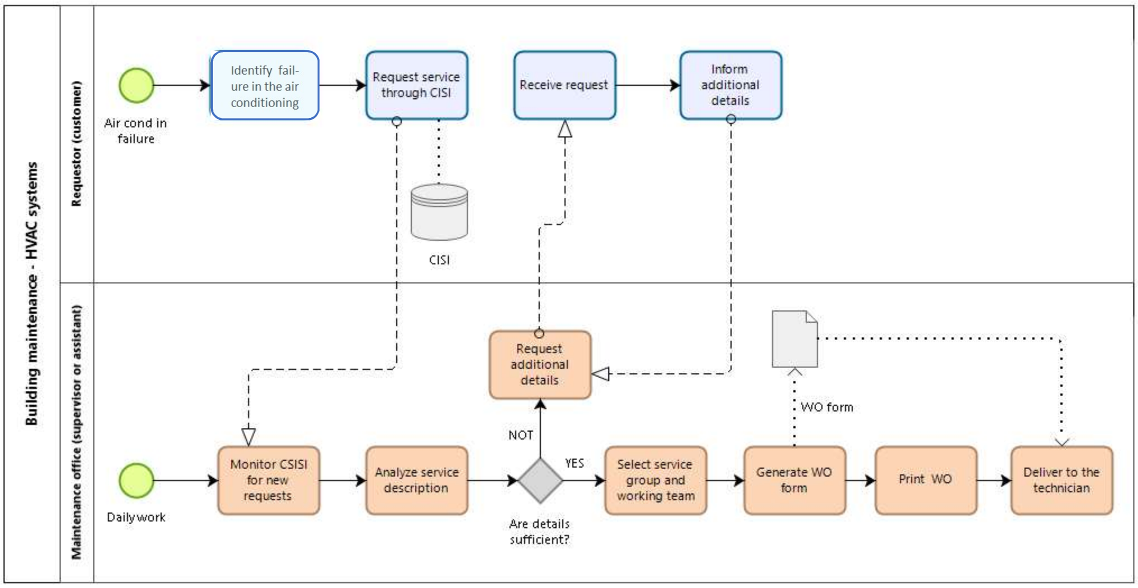

Figure 4. Work orders (WOs) issuance in BPMN.

5.2. Phase II: Requirements Elicitation

As previously stated in the introduction section, the main problem we intend to approach is the limited consideration of a socio-technical perspective in traditional techniques for requirements elicitation. In this sense, this phase aims to gain the necessary data to enhance the CISI, with a socio-technical perspective that focuses on the functional variability and results in more comprehensive requirements, which reflects the breadth and depth of the problem domain.

5.2.1. Data Collection

For this phase, some experts on the subject were interviewed: the process manager, the maintenance supervisor, one assistant, and ten requestors. The data collected in the interviews were recorded as field notes and compiled by the analyst later. The process manager contributed with information related to the basic flowchart, which was built according to BPMN, as shown in the previous section. The remainder of those data were gained from the maintenance supervisor, assistant, and requestors, who reported the everyday work related to work WO issuance. Moreover, observations helped to build the FRAM model, as detailed in the next subsection.

5.2.2. FRAM Model

The FRAM model, as shown in Figure 5, consists of twenty-three functions, which represent the WAD in the issuance of WOs for the maintenance in HVAC systems. The graph shows how the functions' outputs (O) are used by other downstream functions, i.e., input (I), precondition (P), resource (R), time (T), or control (C), creating a link that allows variability spread among functions. Functions exhibiting performance variability have the sign of a sine wave into a hexagon. Background functions are represented as rectangles. This model shows how the functions of WOs issuing interplay with the IT system. Functions depicted in blue are functions performed by the requestor. The others highlighted in green are functions performed by the maintenance supervisor. The yellow function is performed by information technology. Functions performed by the information technology do not present variability themselves; however, the system limitations require several adjustments, which can contribute to undesirable outcomes. Functions depicted with sine wave present potential variability.

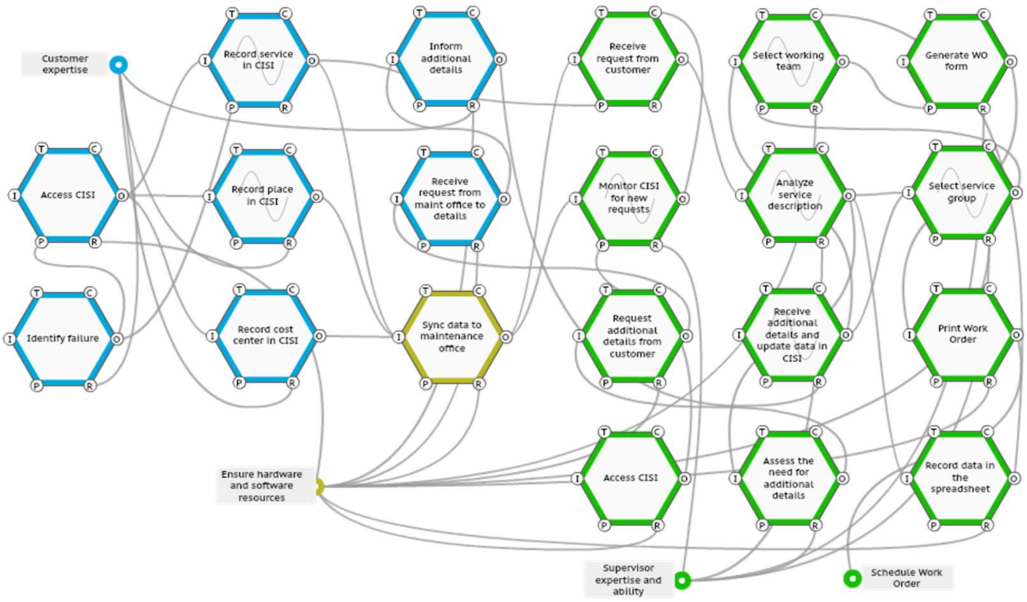

Figure 5. FRAM model of WOs issuance as performed for the maintenance of heating, ventilation, and air conditioning (HVAC) systems in the research & development (R&D) organization.

To request a service, the requestor (customer) accesses the CISI and fills in the data on the screen. Table 1 shows that the function "record place in CISI" has an imprecise output because the requestor may fill the place of service wrongly, which contributes to spreading disturbances in the whole process. In the same way, the function "record service in CISI" affects downstream functions, since requestors often describe the service ambiguously or incompletely because they do have not enough knowledge to describe the service properly. On this subject, when requestors were asked how they perform their task, a requestor said: "*not everyone knows how to fill in the CISI data*". In addition, during the interviews, it was noted that requestors complain a lot about IT architecture. In another interview, the requestor said: "*They ask to describe the type of air conditioning failure [. . .] I don't know how an air conditioning works. They had to send a mechanic here to evaluate the equipment*". A requestor also said that a few years ago, the maintenance workers took a long time to attend to services. In this opportunity, this requestor said: "*I prefer to call the office and ask for maintenance by phone [. . .] I don't like using CISI*".

Table 1. Potential variability identified in the work order issuance for the maintenance in HVAC systems.

Nº	Function	Variability	
		Regarding Time	**Regarding Precision**
1	Record place in CISI	On time This function does not vary regarding time	Imprecise Requestors may fill the place of service wrongly.
2	Record service in CISI	On time This function does not vary regarding time	Imprecise Requestors often describe service in an ambiguous or incomplete way because they do have not enough knowledge to describe the service properly
3	Monitor CISI for new requests	Too late The function can be impacted by delays, since the maintenance supervisor has other assignments out of the office.	Precise This function does not vary regarding precision
4	Analyze service description	Too late This function may consume some time due to adjustments to understand and clarify the service description. This scenario may entail delays in downstream functions.	Acceptable The service description may not be comprehensible by the maintenance supervisor. Then, to clarify the service description, he needs to contact the requestor.
5	Select service group	On time This function does not vary regarding time	Imprecise The unsuccessful outcome in upstream function 5 can entail an imprecise decision regarding the service group.
6	Select a working team	Too late The function triggering time often depends on the availability and qualification of technicians. This scenario submits the maintenance supervisor to trade-offs, since he needs to select an alternative technician.	Acceptable In CISI, the field for technicians' selection does not allow the user to select more than one technician. Then, the maintenance supervisor adapts the WO form, recording the technicians' names in the field "observation".
7	Receive additional details and update data in CISI	Too late Using e-mails or calls to receive a reply can entail delays in downstream functions.	Acceptable Once the requestor's answer is satisfactory, this information is enough to support the service analysis.

As shown in Figure 5, the technological function "sync data to maintenance office" receives input from functions 1 and 2 (see Table 1) and feeds the downstream function "monitor CISI for new requests". This function controls the receiving of new requests. However, as previously disclosed in the preliminary analysis, the maintenance supervisor has other assignments out of the office, which imposes an additional time to achieve the expected result. In the absence of the supervisor, the assistant monitors the CISI and issues WOs. However, he has not the expertise to evaluate the content of the description. This often leads to an adjustment in the way in which these functions are performed. On this subject, during the interview, the assistant said: "*I don't know how to evaluate the type of failure [. . .] I ask technicians for help or I wait for the supervisor*".

In work order issuance, the maintenance supervisor needs to resort to some adjustments during this process due to IT system limitations. For example, the interviewed supervisor reported that the requestor often describes the service in CISI ambiguously or incompletely. In this context, the maintenance supervisor needs to use their expertise and ability to ensure the issuing of WO in the shortest time possible. On this subject, the supervisor said: "*If we were to follow the process through CISI, there would be no time to cope with the occurrence [. . .] Sometimes the customer calls for urgent maintenance. I need to move teamwork to the site quickly [. . .] some situations cannot wait a long time, like a defect in an air conditioning for an important laboratory*".

The function "analyze service description" is considered critical because it is prone to spread variability along with the maintenance working of HVAC systems. In the worst scenario, this function may receive an unsatisfying outcome from the upstream function "receive the request from customer". Table 1 highlights the variability in terms of timing and precision and explains how output variability may lead to resonance in further steps. To damping this outcome, the maintenance supervisor requests additional information about service from the customer. However, using e-mails or phone creates lateness to receive a reply and doubt about whether the requestor received the request for clarification (see Table 1, function 7).

Furthermore, the function "analyze service description" depends on workers' ability to evaluate the request properly. Data from interviews reveals that only the maintenance supervisor has enough expertise to carry out analysis, i.e., this analysis may not be performed satisfactorily in his absence, which can lead to an imprecise output. Therefore, this outcome affects the downstream function "select service group" (see function 5 in Table 1), inducing to select the service group in the wrong way. Consequently, this function acts as a precondition for the downstream function "select working team". In this sense, selecting the service group in the wrong way will cause improper technicians' allocation.

To trigger this function, the maintenance supervisor needs to engage some adjustments during task execution to fill gaps in the information technology and, thus, achieve the desired results. These adjustments are based on their expertise in maintenance activities. As described in Table 1 (function 6), this situation consumes additional time to function triggering, since it submits the maintenance supervisor to trade-offs, due to the need to select an alternative technician. For example, the qualification of each technician, (e.g., a technician trained for working at height), and the balance of workload, acting as criteria for decision-making in allocating team. In this context, the maintenance supervisor uses a spreadsheet on his computer, containing the number of WOs by each technician and the qualification of each one to decide about the team.

As previously stated in the preliminary analysis, in CISI, the field for technicians' selection does not allow the user to select more than one technician. Then, to deal with this limitation, the maintenance supervisor adapts the WO form, recording the technicians' names in the field "observation". However, this scenario can lead to an imprecise output due to misunderstandings or forgetfulness in this step. This may cause further confusion in the maintenance execution.

5.3. Phase III: Requirements Specification

This study aimed to describe the functional requirements for redesigning the IT system (so-called CISI), which is used for issuing WOs for the maintenance of HVAC systems. Then, it presents a level of detail to allow the stakeholders and software developers to understand the SRS document. However, the SRS should not describe any design or implementation details.

Identification of Functional Requirements

As already addressed in the literature, functional resonance concerns the combination of the internal variability of a function with the variability of another function with which it is coupled [64]. Couplings among functions are prone to present variability. Hence, understanding each connection is important for gathering requirements in a better way. Resulting from variability analysis, Table 2 shows the variability identified in the FRAM model, the potential resonance, and mitigating actions.

Table 2. Mitigating actions proposed for potential variability, aiming to establish requirements for redesigning the Information technology (IT) system.

Nº	Function	Variability	Potential Resonance	Mitigating Action
1	Record place in CISI	The requestor fills out specific places for service in the wrong way.	After the WO is issued, it may affect the service performance, inducing the working team to the wrong place.	Perform a survey on all territories of the R&D organization to register all units in CISI. Link each user (requestor) to the places of its operation. This action will decrease manual fills, and consequently, the incidence of fill errors.
2	Register service in CISI	In most cases, the requestor does not have enough knowledge to describe the service comprehensibly.	The incomplete and imprecise description of the service causes variability in downstream functions, because they induce errors in the task, resulting in delays in the maintenance.	Establish procedures in the CISI to facilitate the service description.
3	Monitor CISI For new requests	Competing activities of the maintenance supervisor cause delays to the visualization of service requests. Consequently, it causes a delay in issuing WOs.	May lead to a delay in starting the service.	Assign and train an employee to be responsible for monitoring the requests in the system and for closing the WOs. This action aims to release the maintenance supervisor so that he can exercise the supervisory function of the technicians' work.
4	Analyze service description	The maintenance supervisor contacts the requestor, by telephone, because of a misunderstanding of the service description in the system.	The absence of the complementary contact causes the technician to go to the place of service without adequate information, which can cause delays in the execution and/or rework.	Modify the CISI so that the requester can provide the necessary information for maintenance. Modify CISI to create a communication channel through the system. This avoids contacts by phone or e-mail.
		Lacking analysis or improper analysis.	This situation may cause an error in choosing the service group, and consequently, selecting the working team improperly.	
5	Select a working team	The working team selection depends on the availability and qualification of each professional.	Delay in the start of work resulting from the unavailability of personnel.	The system must count the WOs per professional and indicate to the administrator the amount of each to assist in the decision making of the allocation of team.

This study proposes a set of mitigating actions to prevent potential resonance. Nevertheless, not all translate into requirements, since the current investigation has been focused on prioritizing the situations most affecting the maintenance performance. Additional requirements may be addressed in an upcoming study.

This study specified four functional requirements (FR), as described below. As previously stated, these requirements are resulting in mitigating actions proposed to enhance the CISI. For each requirement, we related the agent, the goal, the detailed description of the requirement, and the outcome, as detailed in Table 3.

- FR 01: Access for the requestor to the CISI
- FR 02: New order for maintenance
- FR 03: Detail of input criteria
- FR 04: Issuance of work order

Table 3. Specification of functional requirements for the redesign of the information technology system used in the issuance of WOs for the maintenance of HVAC systems.

FR01	**Access for the Requestor to the CISI**
Agent	Requestor (User authorized)
Goal	Request for login and password of the requester;
Description	The system must link each requestor registered in the system to the locations of its operation; Show these locations to selection by the requestor;
Outcome	To allow access to the system.
FR02	**New order for maintenance**
Agent	Requestor
Goal	Access to the screen of service request;
Description	By clicking on the "new request" icon, the system must verify the existence of a WO pending final evaluation of the service by the requestor; If there are any WOs, pending final evaluation, the system must communicate this pending WO to the user; The system must display a pop-up notification window for the requester to access the pending WOs and perform the evaluation; When no WO is pending, the system may release the screen for a new request.
Outcome	Release screen of service request.
FR03	**Detail of input criteria**
Agent	Requestor
Goal	Specify criteria for maintenance of HVAC systems;
Description	The system must display a field with "kind of equipment" with the following selection options for the requester: Air conditioner, Refrigerator, Drinker, Freezer; When selecting the "Air Conditioning", the system must offer the following selection options for the requester: Split or Window; The system should display a "Service Type" field with the following selection options for the requester: Installation or Repair; If the requestor selects "Installation", the system must display the options: Do you have wiring? and Do you have a drain system? Each option should exhibit with them checkboxes YES and NO for the requestor's choice; If the requestor selects "Repair", the system must display the "equipment height" field with the following selection options: up to 2 m, 2 to 3 m, up to 3 m.
Description	The system must display a "Failure" field with the following options for selection by the requester: lack of refrigeration, freezing, leakage, noise, equipment does not start, cleaning; The system must display a "best service time" field for the requester to write the best option; Link the selection of air conditioning, refrigerator, freezer, or water cooler to the "HVAC" service group;
Outcome	Service criteria detailed.

Table 3. *Cont.*

FR04	Issuance of work order
Agent	Maintenance Supervisor
Goal	Analyze service criteria pointed out by the requestor and issuing work order;
Description	On the details tab, when clicking, the system must display a report with the input criteria indicated by the requestor; The system must display the technical options registered in each service group; To assign a field to fill with service requirements not detailed by the requestor, but on which the maintenance supervisor deems necessary to perform work; The system must provide, to the maintenance supervisor, a function "send to the customer", which allows the system to notify you of any input criteria not detailed by him, but which were pointed out by the maintenance supervisor during the critical analysis. This communication can be through a message sent to the registered e-mail; The system must account for the quantity of WOs per professional and indicate (to the administrator) the quantity of each one to assist in the decision of allocation of the technicians; The system must allow the WO administrator to select multiple technicians for the work; When the system generates a WO number, it must link this number to the order number of the requestor and display it in the user area; Create a field for the signature of the evaluator of the customer's criteria.
Outcome	Work Order issued.

6. Discussion

As per the description of the service, it can be pointed out that the requestor's inability to describe the problem that requires a maintenance intervention is what causes the most significant effects on the maintenance of HVAC systems because it adds progressive bottlenecks throughout the work. To maintain the work performance, workers engage in several adjustments throughout maintenance, from WO issuance to service end. This explains the reason that overall effects manifest more intensely with work in progress.

In our analysis, the requestor's inability to describe the service properly, aligned with the need for clarification to feed the WO with pertinent details, make this activity relatively difficult and dependent on additional time. In situations of great service demand, mainly of an unscheduled nature, the maintenance supervisor needs to follow these works closely. Thus, as disclosed previously, the assistants assume the activity of issuing the WOs. This situation leads to weaknesses in the WO issuance, since they do not have enough expertise to analyze the requests properly.

During the observations in the WO issuance, we noted that interruptions are common because other workers interrupt them either to gain information about services or request some tools. These disruptions make it difficult for employees to focus on evaluating incoming requests in the CISI. We also noticed that customers impose time pressure on the maintenance supervisor to attend to a request. They call the maintenance office repeatedly, requesting information about their services. Moreover, technicians deliver the spare part listing to the maintenance supervisor verbally or on an improvised sheet of paper. Several times, this resource was what the technician had at the time of work. This act may result in forgetfulness of parts or misunderstanding, and consequently, the sending of these parts to the requester in the wrong way.

The FRAM application allowed the understanding of WAD in the WO issuance and enables eliciting functional requirements for IT system redesign. Examining the FRAM representation, as shown in Figure 5, it is possible to note that FRAM provides more information when compared to BPMN representation in Figure 4. In summation, it is worthwhile highlighting that FRAM focuses on the functions of the system rather than on the components [65]; thus, it provides not only input/output sequences as a flowchart.

Instead, it indicates other relevant relationships, such as resources, controls, preconditions, and temporal constraints, which are unclear in conventional modeling tools for capturing software requirements.

The investigation set out to analyze how people respond to changing conditions, including how variability might lead the system to succeed or fail, aiming therefore to elicit functional requirements to redesign the CISI. However, this study has some limitations. This study exclusively focuses on WO issuance for maintenance in HVAC systems. Although the maintenance of HVAC systems represents an important sample in building maintenance, the participation of only one maintenance type constitutes a major limitation in this investigation. Our findings cannot be generalized to the DBM as a whole. It needs to be extended to the whole DBM to gain additional insights by considering details in the various maintenance types within the DBM.

In terms of analysis, this study has focused on engaging with requestors and the maintenance office workers; however, upcoming research could look at the perspective of other actors who interact with the IT system, e.g., quality manager and IT support, who may point out different functions and features in the IT system. Lastly, the application of FRAM is structurally simple but, due to its theoretical grounding, it requires an initial learning period, summed to a time-consuming application.

7. Conclusions

The research question that motivated this research was how functional variability understanding in the issuance of WOs contributes to the requirements elicitation and specification for the design and enhancement of IT systems that support complex socio-technical systems. This study considered three relevant situations to carry out the redesign of a web-based platform that aims at computerizing requests for building maintenance at R&D territories. The first situation is regarding the service record. The second situation concerns selecting the working team. Finally, the third concerns the WO prioritization. Although three situations were identified, this study focused on the first situation, which is regarding the service description by the requestor, once it was diagnosed as the causal situation most affecting the maintenance performance.

Mainly in socio-technical systems, typical approaches to elicit and specify software requirements are not always sufficient to correctly understand the complexity of IT devices or to anticipate likely error situations. Therefore, this exploratory and empirical study provided a deeper understanding of how the FRAM model can contribute to requirements elicitation and specification. The usefulness of the proposed methodology was demonstrated through a case study in the issuance of WOs for the maintenance of HVAC systems. This study used principles from HFE and Resilience Engineering concepts, mainly regarding the understanding of the variability in complex socio-technical systems. Thus, seeking to describe the WAD as a realistic vision of the process, this approach allowed eliciting and specifying functional requirements for improvement in the IT system. However, this study did not intend to detail the non-functional requirements of the system, which may be addressed in an upcoming study.

Regarding the adopted methodology, the FRAM model was adequate for the research proposal, because it aimed to understand WAD in the context of the study. This study contributes to the development of Software Engineering for application in the work environment. The FRAM model enables us to make inferences from hidden or fuzzy situations that are often not expressed by users of the system or are not detected by the system designer. This study has made evident the need for other studies in the area, allowing the analysis of how the FRAM method can improve the software requirement specifications. Even though the current study has been capable of accomplishing its primary aim, there are suggestions and recommendations for further studies that attempt to improve and broaden this research field. This study may be helpful for other researchers who want to apply the proposed framework for other maintenance types rather than HVAC systems. Moreover, to validate the overall effectiveness of eliciting software requirements with the lens of

HFE and resilience engineering, it could be applied in other complex domains, such as healthcare, aviation, and so forth. Finally, we expected that stakeholders in software design and system engineers may use this study to integrate HFE and Resilience Engineering concepts into the design of software as a standard practice.

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