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.

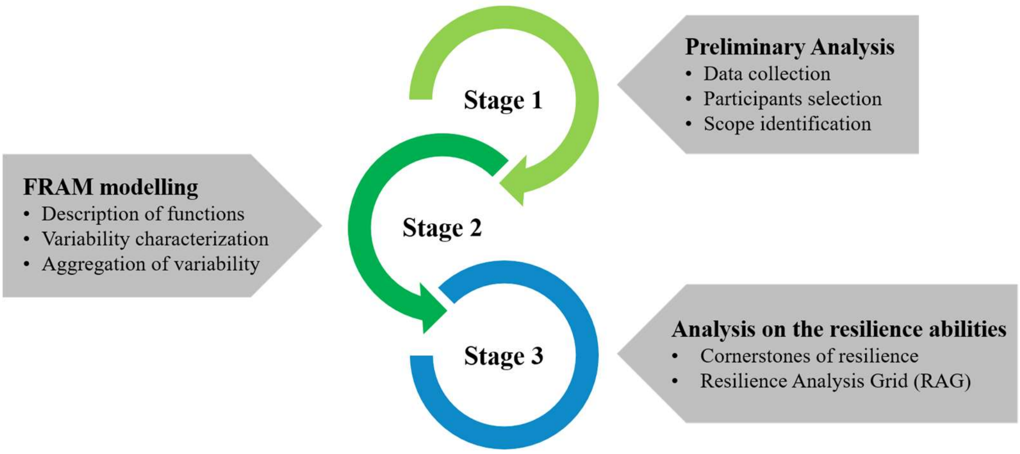

Figure 1. Proposed framework for analysing empirical resilience abilities

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.

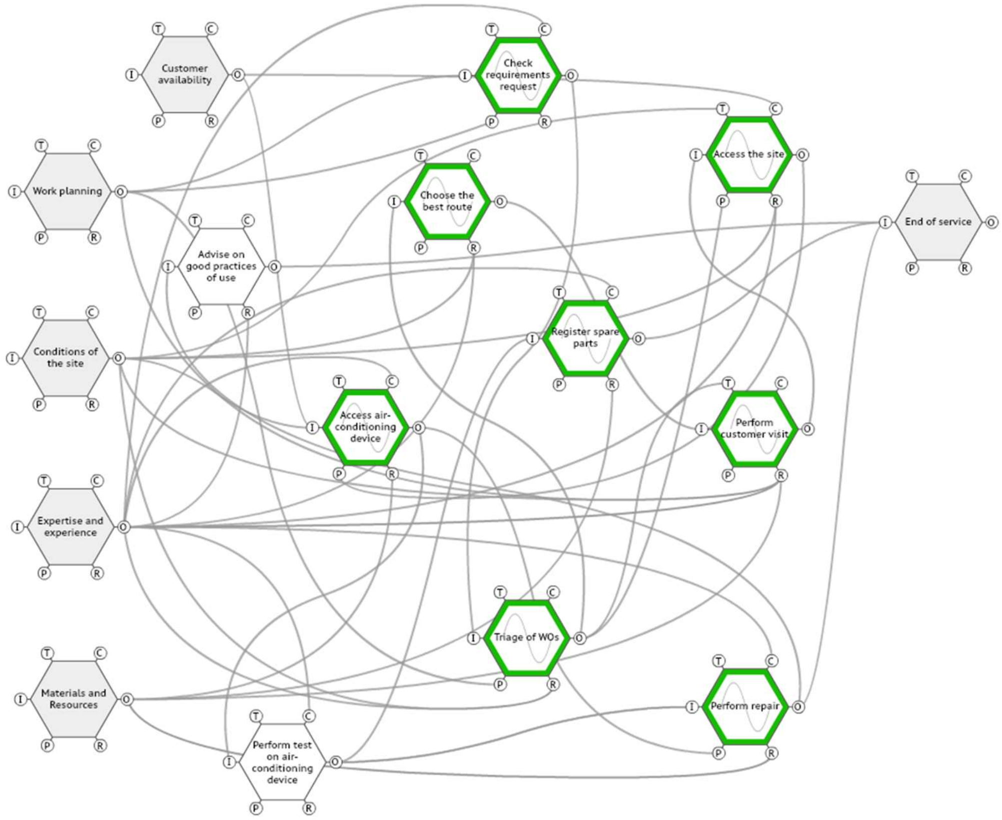

Figure 2. FRAM model for the maintenance of air conditioning devices. Functions depicted in green are functions presenting variability. The other functions depicted in white do not present variability

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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