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LEARNING FROM DELAYS IN DAILY DESIGN WORK – COMPARISON OF ROOT CAUSE ANALYSIS AND FUNCTIONAL RESONANCE ANALYSIS

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ABSTRACT

Procurement and construction work depend on error-free and on-time designs. However, the design process may be erroneous and behind schedule, which often causes cascading delays and problems in the construction process. Hence, when a major delay occurs, practitioners often query the design process, and much time and many resources may be required to find the root cause. However, minor delays and mistakes that occur in everyday work are not usually investigated, even though they can contain information necessary to avoid significant adverse events. This study aimed to determine how three deviations that occurred in a normal, well-progressing project can be investigated using two different methods, as well as the significance of small errors and events in preventing larger errors and events in the future. Root cause analysis and functional resonance analysis were the research methods. The findings of this study showed that slight variability in trivial design and design management tasks generated a considerable number of unnecessary tasks and delays. Therefore, examining variability in the outputs of tasks could benefit designers and design management.

KEYWORDS

design, root cause analysis, Ishikawa diagram, functional resonance analysis, FRAM, RCA

INTRODUCTION

A building project consists of a conceptual design, schematic design and detailed design. Each design discipline considers the others' knowledge, processes and solution proposals in meeting the client's needs and requirements (Wang et al., 2014). The daily work of a designer involves a great deal of technical expertise in the field, which includes many different phases of the design process, such as clarifying tasks, searching intuitively for solutions, working through solution principles and concept options and making various qualitative choices (Robinson, 2012). A significant part of the designer's daily work involves non-technical tasks. such as reporting, personal work planning, information retrieval and social interaction (Hales, 1987). However, the multidisciplinary design process is prone to delays, which can also affect the construction process during the detailed design phase (Pikas et al., 2020).

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Design delays have several adverse effects. Delays in design are a significant risk for construction projects, which can lead to extreme changes in the production phase (Mbachu, 2011). Design delays can also affect the work of the project team by reducing trust among the parties involved (Uusitalo et al., 2019). Therefore, design delays in the construction industry have been studied extensively, and efforts have been made to learn from them through both research and practice.

Root cause analysis (RCA) is a common technique used to learn from mistakes. The goal of RCA is to enable individuals to learn from their mistakes and gain a deep understanding of their root causes (RC), thus preventing their recurrence (Cerniglia-Lowensen, 2015). The target of RCA is to repeatedly ask "why" questions to determine the RC and remove it to prevent the harmful event from recurring. This method is often called the five times why (5 x why) method. By asking at least five times in a row about the RC, the most common and intuitive reason often reveals complex and hidden factors related to the occurrence of the event. RCA has become widespread in research and business. One of the earliest developers and users of this method was Professor Kaoru Ishikawa, who introduced RCA in a factory environment in Japan in the 1940s to improve quality (Doggett, 2005). The most typical graphical use of RCA is the Ishikawa diagram, which is also called a fishbone or cause-and-effect diagram (Ishikawa, 1976). The purpose of the diagram is to describe in an easy-to-understand visual form the reasons that led to a certain consequence and to categorise them systematically. It has been described as a fishbone because of the method analyses the causes of the event, moving from the general (big fishbones) to the specific (small fishbones). Figure 1 shows a typical example of the Ishikawa diagram used in this study.

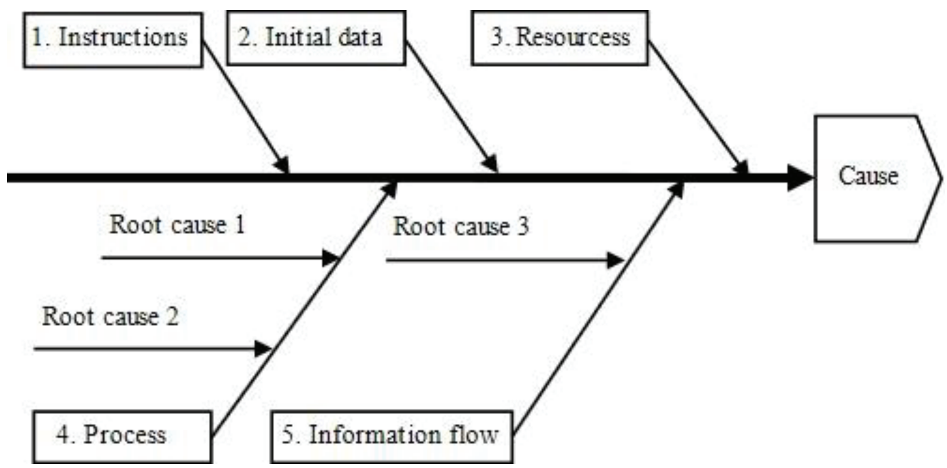

Figure 1: Ishikawa diagram in this study

Ishikawa emphasised the method's potential for learning: simply participating in the creation of the diagram is educational (Martínez-Lorente et al., 1998). However, the RCA assumes that causes or events related to an event are related to each other, and by following these interrelationships, it is possible to determine where the problem originated. RCA has become popular in daily safety work because of its simplified visual representation. Moreover, if the analysis is accurate, it also saves the practitioner's time (Hollnagel, 2017, p. 188). However, problems might arise if the results of a complex world are unclear, meaningless or too difficult to understand. To address such situations, Hollnagel (2017, pp. 30–31) presented a functional resonance analysis method (FRAM) that represents a complex nonlinear approach.

FRAM is based on resilience engineering techniques, which offer an alternative way to evaluate and design complex systems (Rosa et al., 2015). The FRAM and RCA methods can be viewed as a continuum of the domino model, in which events unfold as cause-and-effect chain reactions in which the first domino to fall is the RC (Riccardo et al., 2018). Both methods can be used for the qualitative analysis of outliers, although FRAM itself can also be used to conduct a quantitative analysis (Zinetullina et al., 2021). Hollnagel (2017, p. 40) developed FRAM as a method for analysing past events, like RCA, FRAM can be used to analyse past events as well as probable future events and failures. FRAM is based on four principles: 1) things go right and wrong for the same reasons; 2) sociotechnical systems always adapt to circumstances; 3) observations of results are described as emergent; and 4) relationships and dependencies in the system's functions are described in relation to the development of the situation using functional resonance (Hollnagel, 2017, p. 41). FRAM does not focus on the probability that a single function or task will go wrong; instead, it describes what can happen during typical daily work and how variability affects the situation, either positively or negatively (Rosa et al., 2015). In FRAM, the term *resonance* is an analogy of how variability in everyday events and performance can lead to unexpected results (Adriaensen, 2019). In individual events, such as the quality of the initial information in design work or the communication between designers, there are always natural variability, which can be thought of as vibrations or oscillations, which in a certain situation can increase unexpectedly (i.e., into resonances), thus causing an unexpected event.

The current version of the FRAM process has four stages: the first step identifies the functions that make up the FRAM model; the second step characterises variability in the functions; the third step examines the connections between the functions and determines how variability can lead to an unexpected event; and the fourth step suggests ways to manage and limit the observed variability (Yang et al., 2017). Figure 2 shows a typical FRAM model in which the function is represented as a hexagon from which the functions of the event under study are connected by branches. The process of making a cup of tea is used as an example. The functions are as follows: 1) boiling water; 2) heating the teapot; 3) adding boiled water to the teapot; 4) adding tea leaves to the teapot; 5) placing the lid of the teapot on the pot; 6) steeping and waiting; 7) straining the solid parts of the tea; and 8) pouring the tea into teacups.

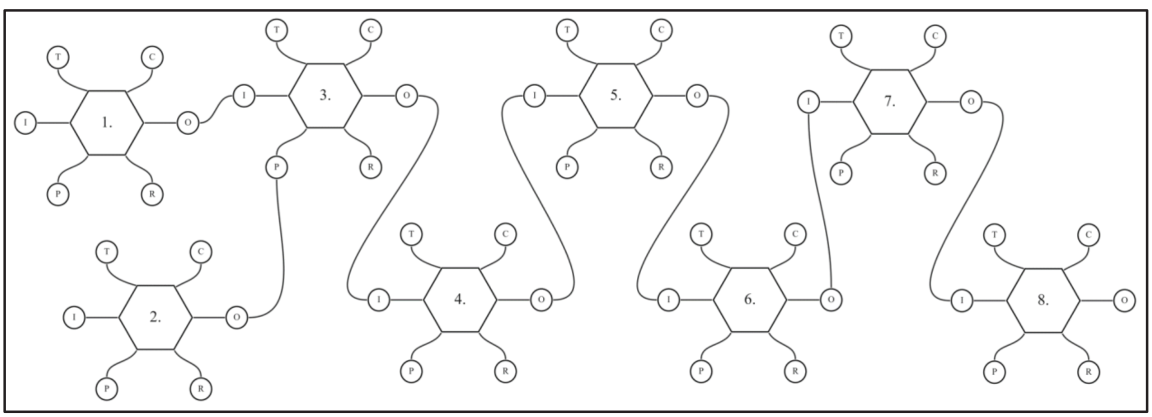

Figure 2: Typical FRAM model of the tea-making process

Variability occurs differently in functions. For example, it can arise from the machine or device used, from human activities or from organisations and social settings (Hollnagel, 2017, p. 100–106). Variability also occurs in the connections between functions, such as input, precondition, resource, control and time (Grabbe et al., 2022). For example, the output can be too fast or too slow, it can be too long or short (e.g., a machined product), it can be the wrong output (e.g., wrong information delivered), it can be too much or too little, it can leave too early or too late, and so on. As shown in the teapot example in Figure 2, the graphic description of even a simple model requires a set of interconnected function hexagons with links, which is difficult to view and interpret. Consequently, FRAM data are typically represented in table form, as in the present study (Saurin, 2016).

RCA is a well-known method used in the construction industry (Hsu et al., 2020), especially in lean construction (Enshassi et al., 2019). In lean construction, RCA is an essential and well-established component of the Last Planner® system (LPS) (Ballard, 2000; Khan & Tzortzopoulos, 2015; Abbasi et al., 2020). However, there is limited knowledge about the benefits of FRAM in the construction industry (Patriarca et al., 2020). Rosa et al. (2015) applied FRAM to identify work-related hazards on a construction site and piloted the method in the construction industry in Brasilia. Saurin (2016) also focused on the safety aspect and used FRAM in occupational safety inspections of data collected from 13 Brazilian construction sites. Ransolin et al. (2020) investigated the interactions between patient safety and well-being in a built environment using FRAM. Del Carmen Pardo-Ferreira et al. (2020) focused on concrete frameworks and modelled successes during a workday using FRAM.

This study contributes to knowledge about the use of FRAM. Neither the RCA nor the FRAM has been investigated comprehensively from a design point of view. Instead, the emphasis of previous studies on both methods has been on occupational safety. However, design work is a complex sociotechnical system that greatly affects many aspects of construction projects, including occupational safety. Therefore, focusing on the use of both the RCA and the FRAM to analyse design work is justified. The aim of this study is to use both methods to determine what can be learned about the effects of small errors and events and how the findings of the RCA and FRAM differ. The selected research approach was exploratory and data-oriented.

METHODS

SOURCE OF THE RESEARCH DATA

Because the goal of the study was to explore and learn from the RCA and FRAM methods, the research was limited to one project and three event chains. Research data were collected from a Finnish hotel renovation site of approximately 40,000 m^2, which, according to the project manager, "proceeded normally on schedule without significant problems." This was one of the basic criteria for the selection of the research site. The researchers were interested in day-to-day design work in a normally running project in which case the events under investigation would not be affected by actions and thoughts caused by major problems. A project management consultant, five design offices and the company responsible for building information model (BIM) coordination participated in the study.

APPLICATION OF ROOT CAUSE ANALYSIS

The RCAs were conducted to explore the cases to gain as many insights as possible. The aim was to gather information on the RCs of delayed design activities and the chain of events that led to delays. Of the 723 tasks in LPS sessions, three were selected for the study and subjected to detailed RCAs. The selection of topics was based on the following four principles: 1) the topic involved one or more delayed design tasks (suitability); 2) the events of the topic were ongoing during the research (timeliness); 3) the project management evaluated the study of the topics to determine their usefulness for the project (practical relevance); and 4) the topics were suitable for research (academic interest). The RCA consisted of four steps: 1) preparation; 2) open group interviews; 3) analysis; and 4) cross-comparison.

RCAs were prepared by consulting plans, meeting minutes and relevant emails. This information was provided by the project management and collected from the project's cloud service. The researcher also received documents and emails forwarded from different stakeholders involved in the project. The collected data were stored in the Microsoft Teams environment and then evaluated in collaboration with the project's management. This procedure was intended to provide a documented understanding of the events leading to the

RCA, in which the researcher relied on oral information from the respondents. The documentary-based researcher's understanding of the events was visualised as a swim lane diagram (Waterhouse, 2021) and sent as pre-material to the respondents. In the interviews, the case was examined using the *5 times why* method, in which the researcher observed and notated the conversations. Several rounds of interviews were conducted to allow for in-depth exploration and clarification of the issues raised.

In the next phase, conclusions were drawn from the analysis of the collected data. The classification of the RCs identified was based on Ballard et al.'s (2007) LPS method, which is commonly used by LPS users. The researchers added a fifth category related to information flow gaps. Finally, the results of the RCAs were cross-compared to find commonalities.

APPLICATION OF FUNCTIONAL RESONANCE ANALYSIS

In the FRAM analysis, the researchers identified the functions of the RCAs and added these to the spreadsheet, including a detailed description of the function and its aspects. The factors that caused variability are presented in Table 2. In this stage, the research was limited to examining only variability in outputs. Based on the table, three visual models with links connecting the functions were prepared. In the final stage, the researchers summarised potential approaches to reduce variability in the studied cases and compared the results of the RCA and FRAM. Figure 3 presents the research design.

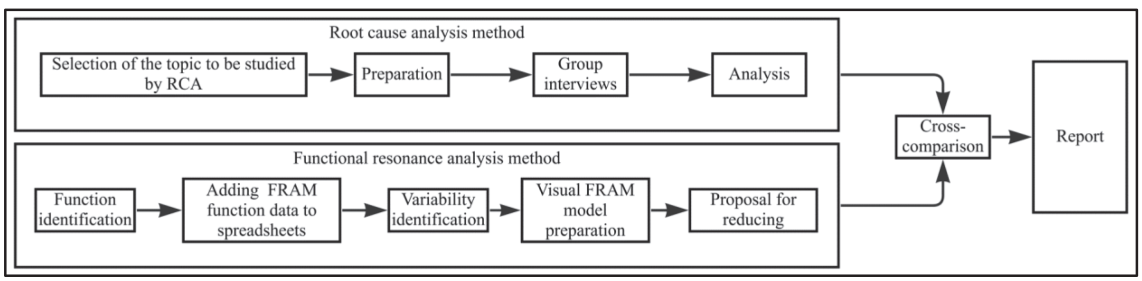

Figure 3: Research design

FINDINGS

FINDINGS OF ROOT CAUSE ANALYSES

The findings of the RCA were classified as chains of events that are represented in an Ishikawa diagram. The researchers reflected on the findings with the project management team, and based on the discussions, the RCs were assessed as appropriate and logical. The Ishikawa diagram of RCA No. 2 is presented in Figure 4.

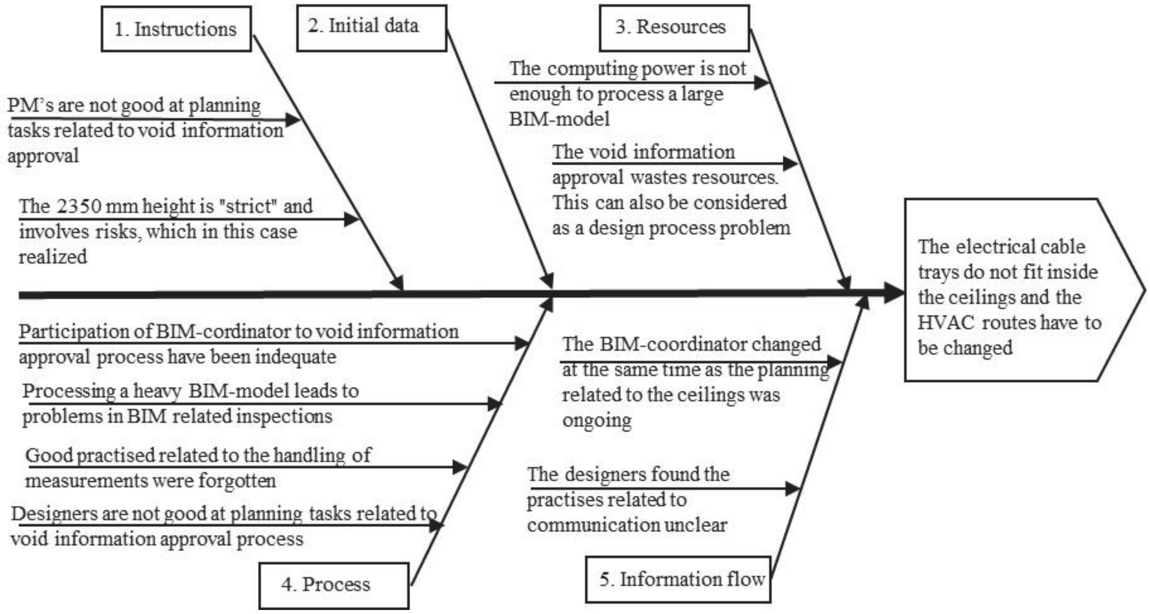

Figure 4: Root cause analysis number 2

Figure 4 presents the RCs that negatively affected the design process. A cross-comparison of RCAs is presented in Table 1.

Table 1: Summary of the Results of the Root Cause Analysis

RCA	Instructions	Initial data	Resources	Process	Information flow
1			X		X
2	X		X	X	X
3	X		X	X	X

Based on the results of the RCAs, all three cases had problems in design coordination, especially in the flow of information between designers. In all three cases, site personnel detected problems that caused stoppages in production. In all cases, there were personnel changes in the project's organisation, which were perceived in the RCA sessions as having a negative effect on the events. This was connected to problems related to the flow of information. In addition, the analyses revealed that the design was not implemented according to the pre-described process, but according to personal experience. Deviation from the process and person-centredness combined with personnel changes affected these three cases.

No observations were made regarding the initial data on the RC. However, in the RCA sessions, the respondents often referred to a lack of initial data. In all RCAs, information about the events was fragmented because it had to be gathered from several sources, and extensive networks of events were formed. The complexity of the relationships between the data and events made it difficult to identify and communicate problems.

Findings from Functional Resonance Analysis

The results of the FRAM analysis are summarised in Table 2, including the functions. Table 3 presents the output variability. Detailed descriptions of the functions have been omitted because of limitations on the length of this short paper.

Table 2: Functions and Output Variabilities

Function	I	O	P	R	C	T	Output variability (qualitative)
Case 1							
1.1 Updating LPS board	X	X	X	X	X	X	Inaccuracy: HVAC designers' task of the ventilation machine serviceability report missing from the LPS board.
1.2. Preparing a serviceability report on the ventilation machine	X	X	X	X	X	X	Late: task started late due to a task missing (serviceability report) from the LPS board.
1.3. Marking the hauling opening in the structural roof plan		X		X	X		Inaccuracy: the plan is updated needlessly, the opening is not necessary, but the data from serviceability report were late.
1.4. Marking the hauling opening in the architectural roof plan		X		X	X		Inaccuracy: the plan is updated needlessly, the opening is not necessary, but the data from serviceability report were late.
1.5. Updating the hauling opening to the structural plan	X	X		X	X		Inaccuracy: the plan is updated needlessly, the opening is not necessary, but the data from serviceability report were late.
1.6. Definition of the construction method (of the roof)	X	X		X	X		Inaccuracy: unclear communication about the construction method; task missing from the LPS board.
1.7. Commenting on the hauling opening	X	X	X	X			Inaccuracy: task for commenting missing from the LPS board
1.8. Removing the hauling opening from architectural plans	X	X		X	X	X	Late: the task was started late because the serviceability report was delayed.
1.9. Removing the hauling opening from structural plans	X	X	X	X	X	X	Late: the task was started late because the serviceability report was delayed.
1.10. Demolition work on the roof	X	X	X	X	X	X	Late: waiting for detailed drawings
Case 2							
2.1 Updating LPS board	X	X	X	X	X	X	Inaccuracy: the void information approval tasks are missing from the LPS board.
2.2 BIM coordination meeting	X	X	X	X	X	X	Inaccuracy: discussion about the unnecessary voids is missing from the BIM coordination meeting agenda.
2.3 Schedule planning for void information approval	X	X	X	X	X	X	Late: schedule planning for the void approval started after the void approval started (approx. eight months earlier).
2.4 Void information from structural designer to HVAC and EIA designer	X	X	X	X		X	Too early: the void information approval started eight months before the real need of the site.
2.5 Void information from HVAC and EIA designer to structural designer	X	X	X	X		X	Inaccuracy: lack of process or instructions for removing unnecessary voids from the BIM models
2.6 Re-routing of duct routs in HVAC BIM model	X	X		X		X	Late: due to the detected rebar on site, the HVAC ducts will have to be re-routed.
2.7 Re-routing of cable trays in EIA BIM model	X	X		X		X	Late: due to the re-routing of the HVAC ducts, the route of the cable trays must be changed.
2.8 Publishing coordination BIM model	X	X	X	X		X	Inaccuracy: Unnecessary voids are not removed from the coordination BIM model.
2.9 Observation of rebars in diamond drilled hole	X	X	X	X	X	X	Late: information about the effects of the rebars in the drilled holes is provided to HVAC and EIA designers when the technical routing was already done in BIM models.
2.10 Publication of the void drawing of the 5th floor roof	X	X	X	X	X	X	Late: HVAC re-routing delayed the release of the floor plan
2.11 Examining the need to change the ceiling height	X	X	X	X		X	Late: HVAC re-routing led to a redesign of the architects ceiling plans

Note. I = Input, O = Output, P = Precondition, R = Resource, C = Control, T = Time, EIA = Electrical, Instrumentation and Automation, HVAC = Heating, Ventilation and Air Conditioning

In Case 1, the recurring sources of variability in function output were the absence of the task from the LPS board, unnecessary design changes and starting the task late. In Case 2, recurring sources of variability were inaccurate because of unnecessary voids, which was related to a lack of process and guidelines for removing them. This issue was not discussed in the BIM coordination meetings because it was not on the agenda. Moreover, during the inspection and publishing of the coordinated BIM model, unnecessary voids were not addressed. A common source of variability in Case 1 was the absence of tasks; in Case 2, void approval process tasks were missing from the LPS board.

Figure 4 shows the functions in Case 1 and the links between them. Although the graphical presentation is difficult to interpret because of the high number of links inherent in complex systems, it is nevertheless possible to observe the central role of the LPS board in this chain of events. The numbering of the functions in the figure corresponds to the numbering in Table 2.

In contrast to Table 2, functions marked “0” have been added to Figure 4; this control function defined cycles of the LPS sessions and board updates, which in this case was the project plan.

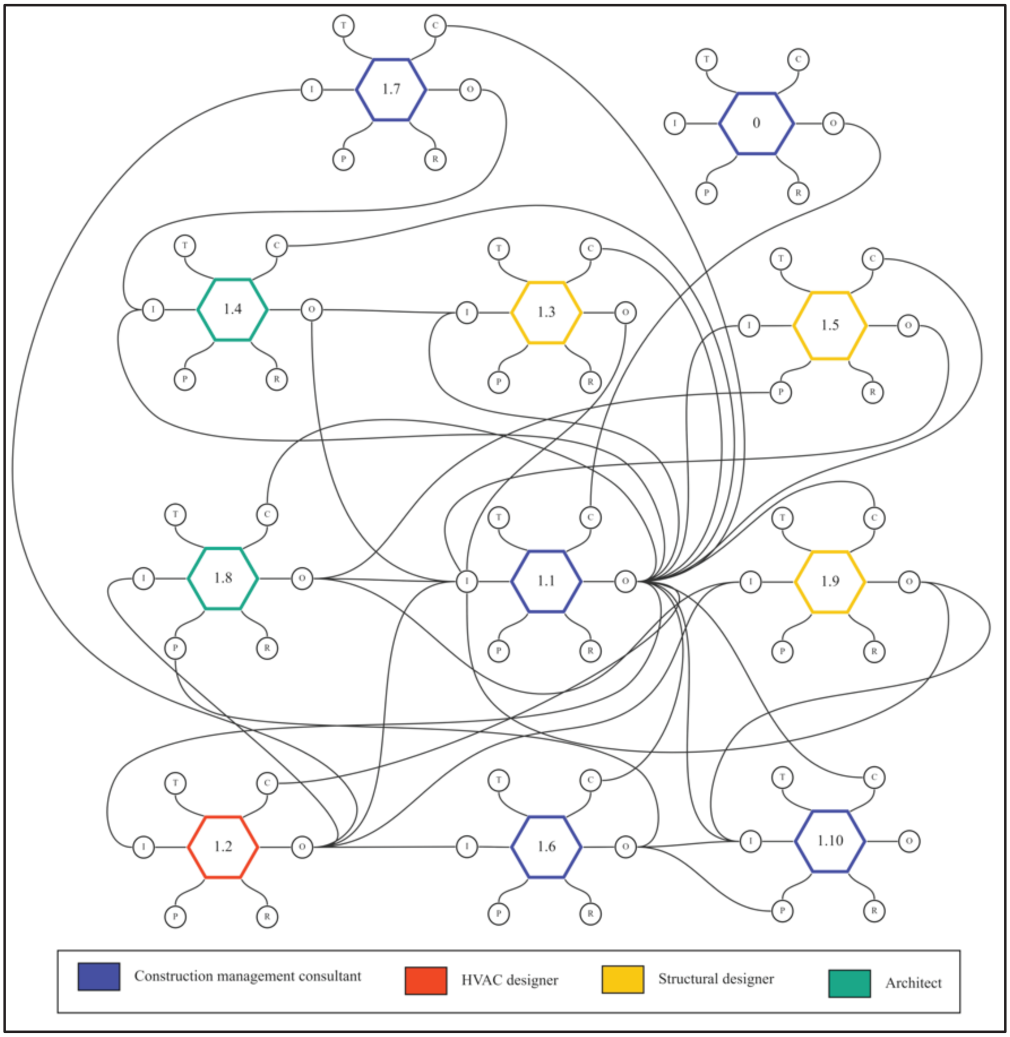

Figure 4: FRAM analysis of Case 1

As shown in Figure 4, colours were added to the functions representing the resources: blue indicates a construction management consultant; red indicates an HVAC designer; yellow indicates a structural designer; and green represents an architect. Table 2 and Figure 4 show the central role of the LPS and the variability associated with the missing tasks.

Summary of Findings

In Case 1, the RCA identified the fragmentation of information into several conflicting documents and a lack of clarity regarding the need to build hauling openings were the RCs of delay. The FRAM identified recurring variability in missing LPS tasks and unnecessary design work, which caused delays. Variability of LPS tasks prevented HVAC reporting functions from being implemented, while other functions in the system (e.g., design tasks and modelling work) continued to progress, causing unnecessary rework later in the project.

In Case 2, the RCA identified the RCs of the delay as follows: the design deficiencies of void approval-related tasks by both the construction management and the designers; the BIM coordinator’s low participation in the void approval process; unclear communication by the construction managers; lack of computing power in the computers used for BIM coordination; insufficient tolerances for the renovation site; deficiencies in the presentation of dimensions in the drawings; and key personnel changes in BIM coordination. In Case 2, the variability identified by FRAM included the following: inaccuracy in the void approval process; and variability in the outputs of the three functions, which can also be defined as incomplete coordination. Time variability occurred in both directions in Case 2: void approval began eight months before the real need of the site, which was too early. Correspondingly, these tasks were planned eight months after the work began, which was too late.

DISCUSSION

The investigation of the RCs confirmed that chains of events in the design process are complex and involve multiple design disciplines (Bertelsen, 2003; Luo et al., 2017). Researching such complex, albeit daily, design-related tasks and chains of events by applying RCA was time-consuming. This may be one reason that learning-from-mistake techniques, such as RCA, are not widely used in construction and design (Dave et al., 2015). However, several interesting results were revealed by the RCAs.

In the RCAs, the initial data usually emerged as the respondents' answers to the first "why" question, but as the analysis progressed, the importance of the initial data decreased. In none of the three cases was the lack of initial data identified as the RC but a consequence of an actual RC. Although the sample comprised only three RCAs, this result was interesting, especially in terms of the typical narrative often heard by project designers, that is, a "lack of initial data". This finding contradicted those of previous studies in which a lack of initial data was often identified as the most important RC in design deviations (e.g., Khan & Tzortzopoulos, 2015; Koskela, 2004). This contradiction raises a question that should be investigated further: Does using RCA lead to a deeper and novel understanding of the RCs of design problems? For example, the event, "the drawings printed from the BIM model are incorrect", which was the cause of the delay found in the RCA, can be first classified as "initial data". However, the event "the BIM model has void reservations that are not needed" can be classified as a "process" because the void approval process was inadequate in this case. The RC was suggested to be the initial data, but after further investigation, the real situation was comprehended by the participants, and the actual RC was changed. This finding is consistent with that of Parchami et al. (2019).

The RCAs also supported previous research on the significance of planning person-centredness and key personnel changes for the success or failure of planning, as in the three cases in the present study. In a construction project, key personnel are subject to turnover, which can have serious effects on its progress (Chapman, 1999). Combined with the turnover of design experts and variability in their expertise (Manavazhi, 2004; Wang & Leite, 2014), the phenomenon observed in the results of the RCA is a model example of the variability related to the resource link used in the FRAM method.

In this study, the basic form of the FRAM was used because the researchers aimed to explore its applicability to design work. The basic form of FRAM has six characteristics: input, output, precondition, resource, control and time. However, as Hollnagel (2017, p. 194) pointed out, nothing prevents the use of other characterisations in applying this method. This freedom creates interesting possibilities, such as in design and lean construction. For example, in design, one characteristic could be value (Salvatierra-Garrido & Pasquire, 2011), and in the context of lean, one characteristic could be flow (Tommelein et al., 2022). Managing variability in these two properties is important for the operation of the system (Mossman, 2018; Lehtovaara et al., 2021). However, when new characteristics are added to the method, it should be considered that FRAM aims to determine how everyday activities are conducted. Therefore, adding, changing or removing characters should not weaken the underlying principle of the method.

Although the application of RCA and FRAM to the same chain of events yielded differing results, combining these methods could improve learning from mistakes in the construction industry. For example, the reason for the low use of RCAs (Dave et al., 2015) could be that a conventional construction project involves several tasks. On average, two-thirds of LPS tasks are completed on time (Aslam et al., 2020). Hence, when LPS is used, an RCA should be performed on one-third of the activities each week. In the example used in the present study, the LPS board contained 723 tasks, of which, according to the above principle, 241 RCAs would be performed. One author of this paper used four RCAs in his entire master's thesis. Therefore, it would have taken the working hours of 60 master's degree students to study two-thirds of the delayed LPS tasks in this hotel project, which is too much work to achieve an accurate and precise RCA. Could the FRAM perspective, which focuses on reducing variability in functions and the links between them, be a less resource-intensive way to learn from mistakes? Alternatively, could a FRAM analysis of RCA practices in the LPS session help better understand why RCA is so time-consuming? These questions and the use of FRAM in practice should be investigated further in construction studies.

CONCLUSION

This study applied the FRAM and RCA methods to two chains of events in design work. The findings showed that variability in event chains may have potential importance for the construction industry. The findings on the use of RCA and FRAM differed, which raised the question of whether the joint application of these methods could lead to learning from mistakes in the construction industry. The systemic perspective of the concept of variability in FRAM revealed aspects of the process that differed from traditional RCA. This focus on the variability of FRAM may be useful for lean construction researchers and practitioners, although further research and experiments are needed. A significant limitation of this study was the limited amount of data on only two chains of events in one geographically limited renovation project. Future research is recommended to explore a larger amount of diverse data (both by project type and geography), which could yield a more holistic picture of the RCs of design delays and provide further insights into their analysis. Further limitations are that the FRAM was focused on learning in daily work, which was hindered by the retrospective approach used in this study. Regarding learning from variability in daily work, FRAM may facilitate researchers and practitioners because the method does not require the existence of faults, errors or delays, which may enable the discussion of systemic problems without feelings of guilt, which often hinder the use of RCA.

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