Method Article

A dynamic version of the FRAM for capturing variability in complex operations

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\textbf{ABSTRACT}

Functional Resonance Analysis Method (FRAM) is a function-based approach to model complex socio-technical systems and to manage variability. The current FRAM related tools are unable to capture qualitative and quantitative characteristics of variability as well as temporal variations. This study presents in detail a dynamic FRAM-based tool, which is called DynaFRAM. It is introduced to address the variability-related deficiencies of the FRAM related tools. It aims to capture variability in complex operations. It is a dynamic tool developed to capture time related variations in complex operations. This increases the attractiveness of the DynaFRAM for complex operations where specialists and practitioners make decisions in complicated situations. The ability of the DynaFRAM is demonstrated by examining a healthcare related case study. Although the ability of the DynaFRAM is assessed through capturing variations in healthcare operations, it can be applied to other domains in a similar manner.

- The DynaFRAM is a dynamic FRAM-based tool.
- It is able to captures different characteristics of variability.
- It facilitates understanding and analysis of variability in complex operations.

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Specifications table

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Background

Functional resonance analysis method (FRAM), developed by Hollnagel [1], is a method that provides the possibility of constructing a functional model, including two major parameters: functions and variability [1]. Mapping functions helps explain the potential functional pathways in an operation and understand the connectivity of the work in the operation [2]. The concept of variability emphasizes that the nature of the outputs of functions is variable [3]. Modeling socio-technical systems in terms of functions and variability provides valuable insights that can be helpful in safety management of complex operations [4].

Variability is deviations observed in the outputs of functions or the outcomes of the entire system [1,5]. It represents a normal, essential part of work and reflects the need to cope with unstable working conditions [1]. The variability and adjustments of a function can affect other functions and thereby the activity as a whole. Functions can mutually dampen each other (absorb variability), so that the situation can become stabilized. They can also mutually reinforce each other (amplify variability) so that the situation becomes unstable and leads to unexpected and usually unwanted results [1]. Therefore, variability can lead both to positive (successful) and negative (unsuccessful) outcomes [1,6].

The FRAM has been widely used for pursuing different purposes in various fields, such as healthcare, aviation, maritime, railway, environment, and process industries [7,8]. According to Ransolin et al. [9], the FRAM can provide a basis for modeling functional requirements and supporting resilient performance analysis in an intensive care unit (ICU) within the healthcare sector. It can also help understand the influences of information propagation and take advantage of functional properties in the cockpit environment of an aircraft [10]. It also has been applied to maritime activities according to [11,12]. FRAM has been combined with other methods to address industrial problems. Li et al. [13] employed the FRAM with the Accident Causation Analysis and Taxonomy (ACAT), introducing a framework for identifying and analyzing operational risks. Studic et al. [14] introduced a framework based on FRAM and grounded theory for improving the safety management of ground handling services.

Despite the wide application of the FRAM in different disciplines and its central role in functional analyses, it suffers from capturing and visualizing the variability of functions [15,16,6,17]. Capturing variability is of great importance as the variability of coupled functions can amplify each other and result in unwanted outcomes and serious accidents [1]. There are a few tools to support the FRAM method: FRAM Model Visualizer (FMV) software developed by Hill and Hollnagel [18], FRAM Model Interpreter (FMI) developed by Hollnagel [19], and myFRAM developed by Patriarca et al. [20] are three well-known examples of FRAM related tools. The characteristics of the tools are presented in Table 1. The FMV software is a powerful tool to model complex socio-technical systems [18]. The FMI is used to interpret a built FRAM model and help determine how an explained

| Tool                        | Modeling | Interpretation | Variability | Dynamic |
|-----------------------------|----------|----------------|-------------|---------|
| DynaFRAM                    |          |                |             |         |
| FRAM Model Visualizer (FMV) | ✓        |                | ✓           |         |
| FRAM Model Interpreter (FMI)|          |                |             | ✓       |
| myFRAM                      | ✓        |                |             |         |
activity or task may develop [19]. The myFRAM is another powerful tool developed to support the constructing process of a FRAM model [20]. As shown in Table 1, the three developed tools provide some support to model complex socio-technical systems and interpret the constructed models. The focus of the tools is not on capturing and visualizing variability, although performance variability is a key principle of the FRAM method [21,22]. The DynaFRAM is introduced to help understand variability in complex operations. It provides a way of visualizing and understanding qualitative and quantitative characteristics of functional variability. It is also able to visualize performance variability for different cases. Additionally, it is capable of characterizing variations related to instantiations or functional pathways that produce the outcome(s) of the entire system. Moreover, it is able to capture temporal variations related to functions and the entire system. An instantiation characterizes how many functions and which functions are involved in the pathway that each case takes. In this study, an instantiation refers to the experience of a frail patient during transition from hospital to home.

The main objective of this study is to introduce a dynamic FRAM-based tool with the purpose of capturing different characteristics of variability, in order to provide adequate support for the analysis and management of complex operations. The dynamic FRAM-based tool presented in this study can be effective in three ways: (i) capturing and visualizing the qualitative characteristic of variability of functional outputs and instantiations/pathways that produce outcome(s) of the entire system; (ii) capturing the quantitative characteristic of functional variability; and (iii) capturing temporal variations regarding both functions and instantiations.

Methodology

FRAM

The FRAM includes four steps. The first step is to identify functions of the system under study and to describe the functions based on their aspects [1]. Each function can have six aspects as follows:

- **Input (I):** something that starts a function.
- **Output (O):** it is the outcome(s) or result(s) of a function. When a function is carried out, outputs are produced. The outputs can influence the outputs of other functions in maximum five different ways (input, precondition, resource, control, and time).
- **Preconditions (P):** conditions that must be met before a function begins. Preconditions do not start a function.
- **Resources (R):** what a function consumes or requires for producing an output or outputs.
- **Time (T):** temporal restrictions that influence a function (starting time, finishing time, and duration).
- **Control (C):** that monitors or regulates a function.

After identifying functions and describing their aspects, the variability should be captured and characterized [1]. It refers to the variety of ways that the output(s) of a function can be produced (step 2). The third step is to show the aggregation of variability (functional resonance). It refers to variations related to coupled functions. The variability of upstream functions can influence downstream functions, and the whole system performance can be affected as a result [2]. The fourth and final step is associated with identifying the proper approaches for monitoring the system, controlling its variability, and suggesting possible safety barriers [1]. It is noteworthy that the FMV software was developed to model complex socio-technical systems [18].

DynaFRAM: a dynamic FRAM-based tool

A dynamic FRAM-based tool, called DynaFRAM, was developed through programming in the Python programming language. It was developed to cover the variability-related deficiencies of the FRAM related tools described in the Background section. The DynaFRAM tool allows capturing and visualizing variations that occur both in the outputs of functions and in the outcome(s) of the entire system. The DynaFRAM aims to visualize what is produced at the end of a function, when it occurs, and for how long it occurs. Another advantage of developing the DynaFRAM is to provide more flexibility for users to generate scenarios and capture temporal variations both in the outputs
of functions and in the outcome(s) of the entire system. The DynaFRAM is able to capture and visualize functional outputs at a specific period of time when operations are performed. Recording instantiations of variability is possible with the DynaFRAM if the data of more samples are collected in real operations (work-as-observed). A general view of the DynaFRAM tool is illustrated in Fig. 3.

Pseudo-codes presented in Figs. 1 and 2 show how to capture time for an instantiation. The pseudo-code shown in Fig. 1 is for uploading a FRAM model and starting video recording for capturing the time of an instantiation. First, it is checked to ensure a model is uploaded. Then, a class is called to calculate time by a timer. Time is recorded for an instantiation through the pseudo-code presented in Fig. 2.
Fig. 3. A general view of the DynaFRAM tool.

Fig. 4. The comprehensive FRAM model of the hospital-to-home transition process for frail older patients built by Salehi et al. [23].
Table 2
Categorizing patients in the format of scenarios.

| Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 | Scenario 5 | Scenario 6 |
|------------|------------|------------|------------|------------|------------|
| Patient 1 of city 1 | Patient 3 of city 1 | Patient 1 of city 2 | Patient 2 of city 2 | Patient 1 of city 3 | Patient 2 of city 3 |

Modeling complex operations

This study attempts to capture variations in hospital-to-home transition processes of frail patients as a demonstration of the incremental improvement of the DynaFRAM compared to other FRAM related tools. In this section, the steps of model generation with the FMV software are described. Then, the method of importing the FRAM model into the DynaFRAM tool is described, along with an example of how a specific patient instantiation is treated in DynaFRAM. The method used to characterize variability is explained with the aid of examples.

A model of complex operations constructed by the FMV software

The FMV software was used to build a functional model of a complex healthcare operation. A functional model involves function identification, function description, and relationship specification. Fig. 4 shows the FRAM model of a hospital-to-home transition process for frail older people built by Salehi et al. [23]. The FMV software was employed to model the transition process. The model illustrates functions constituting the transition process for frail older people. The functions shown in the model could be executed while a case (frail patient) is transferred from hospital to home. In fact, the model involves the potential functions that each case (frail patient) might pass through to transit from hospital to home. It includes 38 functions starting from introducing a patient to hospital to readmitting the patient (Fig. 4).

Using the DynaFRAM in practice

The applicability of the DynaFRAM for visualizing and capturing variability is evaluated through its use in healthcare operations. The transition process of frail patients from hospital to home is a complex operation, which requires the use of a systemic approach to understand interactions between different elements, including healthcare providers, patients, and caregivers. The capability of the DynaFRAM tool was tested in the transition process of frail patients. Data related to six frail patients during the transition process from three hospitals in Canada were collected (Table 2). It is also able to identify functional interdependencies and to capture functional variability.

In the current study, the DynaFRAM was applied to the transition process with the aim of capturing and visualizing different types of variability in order to enhance the transition quality of frail patients. The first step is to upload the FRAM model of the transition process, which was built with the FMV software by Salehi et al. [23] (Fig. 4). The DynaFRAM tool does not produce a model, but employs the models produced with the FMV software. Fig. 5 shows a FRAM model of the transition process imported into the DynaFRAM tool. As shown in the figure, each function is distinguished with a unique number. The unique numbers are useful replacements for long names of functions, particularly in scenarios. The next step is to upload a scenario related to a patient, which includes the data associated with different functions involved in the transition process of the patient. Table 2 identifies 6 transition scenarios, one each for 6 patients. The information for Scenario 3 (patient 1 from city 2) is presented in Table 3. “Time” (needed for executing a function), “active function”, “active function output”, “downstream coupled function”, and “coupled function aspect” constitute a scenario in the DynaFRAM, as shown in Table 3. It is noteworthy that time unit used for executing functions of all six scenarios is second. The information of other scenarios related to other patients is presented in Appendix A. After uploading the model and the relevant scenario, the model can be run. As shown in Fig. 3, the “Play” button allows running a model in the DynaFRAM tool.
Fig. 5. The transition model imported in the DynaFRAM tool.

Table 3
The information of Scenario 3 provided for patient 1 of city 2.

| Time | Active function | Active function output | Downstream coupled function | Coupled function aspect |
|------|-----------------|------------------------|-----------------------------|------------------------|
| 1    | 25              | Fractured left ankle and fracture of left distal tibia           | 6                           | I                      |
| 2    | 6               | Referral to a geriatrician                                      | 5                           | I                      |
| 3    | 5               | Long background review                                         | 7                           | I                      |
| 15   | 7               | Almost 12 days                                                  | 8                           | I                      |
| 27   | 8               | Hospitalizing at geriatric unit                                | 22                          | I                      |
| 28   | 22              | Left distal tibia/Atrial fibrillation                          | 35                          | I                      |
| 29   | 22              | Nurse assessment                                               | 2                           | I                      |
| 30   | 2               | Satisfactory                                                   | 35                          | P                      |
| 31   | 22              | SW assessment                                                  | 11                          | I                      |
| 32   | 11              | Satisfactory                                                   | 35                          | P                      |
| 33   | 22              | Physiotherapy                                                  | 1                           | I                      |
| 34   | 1               | Wheelchair is required                                          | 35                          | P                      |
| 35   | 22              | Occupational therapy                                           | 21                          | I                      |
| 36   | 21              | Satisfactory                                                   | 35                          | P                      |
| 37   | 22              | Recreation therapy                                             | 23                          | I                      |
| 38   | 23              | Satisfactory                                                   | 35                          | P                      |
| 39   | 22              | Dietitian assessment                                           | 24                          | I                      |
| 40   | 24              | Satisfactory                                                   | 35                          | P                      |
| 41   | 35              | Wheelchair/blister pack                                        | 0                           | I                      |
| 42   | 35              | Informing for discharge                                        | 26                          | I                      |
| 43   | 26              | Spouse/son                                                     | 0                           | P                      |
| 44   | 0               | Acceptable ability for discharge                               | 4                           | I                      |
| 45   | 4               | Extra Mural Program with a physiotherapist                     | 14                          | I                      |
| 46   | 4               | Wheelchair/blister pack/no discharge planner (case coordinator) | 3                           | I                      |
| 47   | 14              | Physiotherapist visited the participant in their home          | 3                           | I                      |
Results and discussion

Operations can be monitored for understanding the performance of the entire system once the functional model is constructed [2]. Constructed FRAM models provide a basis for identifying the potential pathways of both successful and unsuccessful operations. Capturing and interpreting performance variability helps understand the ways that outcomes of a system (successes and failures) are attained. This study strives to capture qualitative, quantitave, and temporal characteristics of variability with the DynaFRAM. A healthcare-related case study was chosen to demonstrate the capability of the DynaFRAM in characterizing and capturing variations. The following subsections include the description and discussion of capturing variability with the DynaFRAM.

Capturing qualitative characteristic of variability

The qualitative characteristic of variability can be captured both for functional output(s) and for the outcomes of the entire system with the DynaFRAM. In this subsection, both states are described and discussed.

Capturing functional output variations is of great importance as the variability observed in the output(s) of a function can affect the output(s) of downstream functions. The outcome of the entire system may consequently be affected with the variability of coupled functions. The DynaFRAM provides a possibility to capture and visualize functional output variations. In this section, the variability regarding qualitative functional outputs is discussed. The DynaFRAM helps understand why the nature of functional outputs is variable. The output(s) of a specific function can be variable for different cases. This is characterized through comparing the output(s) of a specific function for different cases. To this end, the transition model (Fig. 5) should be run for each case/patient based on the scenario provided for that patient. Figs. 6a–6f illustrate the output of <Discharge the patient> function for six patients in the transition process. A comparison of functional outputs visualized in Figs. 6a–6f shows the output of the function is variable for the six patients in the transition process. This example demonstrates the capability of the DynaFRAM in visualizing qualitative functional output variations.

Another advantage of using the DynaFRAM is to record instantiations in order to capture qualitative characteristics of variability between recorded instantiations. In this study, the process of transitioning a frail patient from hospital to home is considered an instantiation. The functions that are executed for each case specify the pathway of that case. The DynaFRAM is able to identify active functions involved in each instantiation. Inactive functions are also identifiable for each case. Two instantiations associated with two patients are presented in Figs. 7 and 8. The number of active functions that patient 1 from city 1 passed through during the transition process is 25 (Fig. 7), whereas the number is 18 for patient 1 from city 2 (Fig. 8).

Processes can be mapped and instantiations can be recorded with the DynaFRAM to capture the variations associated with the outcome(s) of the entire system. A comparison of instantiations characterizes the range of variability in the recorded instantiations. As illustrated in Figs. 7 and 8, the pathway of patient 1 from city 1 is different from the one that patient 1 from city 2 experienced. That is, the two instantiations included different active functions with different functional outputs. The instantiations show that the two patients experienced different paths and their transitions ended up in different functions with different outcomes although both started from the same function. Using the DynaFRAM allows mapping processes and recording instantiations of variability that improves tractability of complex operations. The results showed that the transition process of patient 1 from city 2 resulted in going home and staying there (Fig. 8), whereas patient 1 from city 1 was readmitted to the hospital (Fig. 7). Variability regarding functional pathways or instantiations provides required information to analyze the outcomes of an entire system. Analyzing the variability captured in functional pathways can provide insight into complex operations and help healthcare providers and operations managers to manage better processes.
Capturing the quantitative characteristic of variability

The output(s) of a function may be quantitative or numerical. The number of medications that a patient should take is an example of a quantitative functional output. Understanding the variability of quantitative functional outputs is as important as qualitative functional outputs. To capture the quantitative characteristic of variability, numerical functional outputs should be specified. In this study, numerical dissimilarities and differences in functional outputs are indicative of quantitative variability. The DynaFRAM is able to characterize dissimilarities in the quantitative dimension of functional outputs. To this end, the transition model was run with DynaFRAM for the six patients in order to characterize the number of caregivers that accompanied each patient during the transition process. The results are shown in Figs. 9a–7f. As illustrated in the figures, the functional output of Function 26 (<invite a family member/caregiver>) is variable as the number of caregivers is different for various patients: two caregivers for three patients (Figs. 9a, 9c and 9f) and one caregiver for three patients (Figs. 9b, 9d and 9e). Capturing quantitative characteristic of variability can help analysts identify the sources of variability that influence the output(s) of downstream functions and even the outcome of the entire system.

Capturing temporal variability

Variability might occur because of time pressure as time variations can affect the output(s) of functions or the outcome(s) of the entire system [3]. The DynaFRAM is able to capture temporal variations both for a specific function and for the entire system.
Videos 1–3 in Appendix B show time captured to execute <Add the patient to a waitlist for admission> function (Fig. 5: Function 7). As shown in the videos, the execution time of the function is variable for the three patients: 12 time units for patient 1 from city 1 (Scenario 1), one time unit for patient 2 from city 2 (Scenario 4), and five time units for patient 2 from city 3 (Scenario 6). This temporal variability may affect downstream functions in the transition process of each patient, and may even influence the outcome of the entire system.

The DynaFRAM permits the execution of a FRAM model for different cases. The outputs of functions may be variable when different cases are executed, and only some functions may be carried out at a specific time. An instantiation of an event can be recorded through tracking the variable processes over time. Two recorded instantiations are presented in the format of video in Appendices C and D for patient 1 from city 1 (Scenario 1) and patient 1 from city 2 (Scenario 3). As shown in Videos 4 and 5 (Appendices C and D), time was captured for the instantiations with the DynaFRAM based on the scenarios provided for the two patients. The information of Scenario 1 (patient 1 from city 1) is presented in Appendix A and the information of Scenario 3 (patient 1 from city 2) is shown in Table 3. The transition time captured for patient 1 from city 1 was 73 time units (seconds) whereas the transition process lasted 48 time units (seconds) for patient 1 from city 2, as shown in Figs. 7 and 8. The temporal variability observed in the transition processes of the two patients resulted from different time values recorded for executing the active functions of the two instantiations. Understanding temporal variations in the transition processes can help healthcare providers to improve the quality of care for frail patients.

**Study limitations**

This study had two limitations that should be mentioned. The ability of the DynaFRAM tool was assessed to capture different characteristics of variability in healthcare operations. First, the information used in this study was limited to just six patients although in-depth data were gathered for each patient. A bigger sample size could be a better and more accurate examination for evaluating the capability of the tool in capturing variability. The second limitation was associated with quantitative functional outputs. The outputs of functions for all six patients were qualitative except the output of Function 26 (<invite a family member/caregiver>). This limitation was a barrier in showing the ability of the DynaFRAM in capturing quantitative characteristics of variability.
Fig. 8. Pathway/instantiation for patient 1 from city 2.

Fig. 9. (a): Patient 1 from city 1.  
(b): Patient 3 from city 1.  
(c): Patient 1 from city 2.  
(d): Patient 2 from city 2.  
(e): Patient 1 from city 3.  
(f): Patient 2 from city 3.
Conclusion

The DynaFRAM, a dynamic version of the FRAM, was developed and applied to healthcare operations to investigate performance variability in complex operations. It is suitable for studying and analyzing complex operations characterized by functions. In this study, the DynaFRAM was applied successfully to a transition model of frail patients to capture and visualize different characteristics of variations. The results showed the incremental improvements of the DynaFRAM compared to other FRAM related tools. According to the results of this study, the DynaFRAM was able to capture the qualitative characteristics of variability regarding functional outputs and the outcomes of the entire system. Another benefit of using the DynaFRAM was to capture quantitative characteristics of variability in complex operations. Another benefit of the DynaFRAM was demonstrated through capturing temporal variations both in functional outputs and in the outcomes of the entire system. The application of the DynaFRAM to complex operations enables gaining operational insight that can improve experts’ understanding of the operations they manage.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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