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FRAMalyse: an open tool to quantitatively analyze and evaluate the characteristics of models derived by the Functional Resonance Analysis Method

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As modern socio-technical systems become increasingly complex, there is a growing need for innovative risk and safety management models and methods. The Functional Resonance Analysis Method (FRAM) is a recent approach designed to address this complexity. Interest is rising in expanding the capabilities of software tools that support FRAM analyses. Four well-known examples of FRAM-related tools are the FRAM Model Visualizer, the FRAM Model Interpreter, myFRAM, and DynaFRAM. These tools aid in modeling, simulation, visualization, and interpretation of system variabilities. However, they often lack a user-friendly interface for effective practical analysis and evaluation of a FRAM model's characteristics as well as communication of analysis results. To address this gap, this paper introduces a new open software tool—FRAMalyse. Developed to enhance the quantitative analysis and evaluation of FRAM models, FRAMalyse is particularly useful for managing the complexity of large-scale FRAM models. This initial version aims to empower practitioners and decision-makers to explore FRAM models systematically, efficiently, and effectively, potentially increasing the adoption and usability of FRAM across different domains and industries. The paper explains the functionalities of FRAMalyse, provides application purposes, and gives an outlook for possible enhancements in the future.

Keywords: FRAM, resilience engineering, sociotechnical system, complexity, safety management, software.

1. Introduction

The scientific study of safety and risk can be divided into three distinct "ages" due to the evolving nature of systems (Hale & Hovden, 1998). The first age, known as the age of technology, spans from the early 1900s to the Second World War, focusing on technical measures to prevent mechanical and technical failures. The second age, the age of human factors, introduced the consideration of human performance, primarily seen as a limitation in safety and risk management. Finally, from the 1990s onward, the age of safety management emerged, addressing complex sociotechnical systems (STS). This era recognized the complexity of systems and moved away from an exclusive focus on individual error, instead highlighting the roles of multiple actors at all levels of a system and understanding system success and failure as emergent properties shaped by the interdependence of system elements and socio-technical factors.

This historical development points out two fundamental concepts concerning safety: safety-I and safety-II (Hollnagel, 2014). Safety-I, as the traditional safety approach, follows Newtonian reasoning (Dekker, 2011) and a mechanistic worldview (Heylighen, 1989) relying on reductionism and decomposition. It assumes systems are simple, linear, decomposable, well-understood, and designed, with elements functioning in a predictable, bimodal way. From this perspective, adverse outcomes are attributed to technical, human, or organizational failures, which effective barriers should eliminate or prevent. Humans are viewed as liabilities, and performance variability is something to be avoided. However, modern STS are increasingly non-linear, dynamic, and complex, involving many interacting agents with patterns that are difficult to identify (Perrow, 1984). This complexity necessitates a shift towards Safety-II, which views humans as an essential resource for system flexibility and resilience in the face of uncertainty, where performance variability should be monitored and managed. From this standpoint, risk and safety management should focus on the interactions between individuals and their variability rather than on individual behaviors and reliability (Patriarca et al., 2017b). This paradigm shift toward systems thinking and resilience engineering (Hollnagel et al., 2006) calls for a holistic view that examines "work-as-done" rather than "work-as-imagined”, emphasizing the adaptive capacity of the “mechanisms” that enhance system resilience (Patriarca, 2017). This resilience refers to the system's ability to adapt its functioning before, during, or after changes or disturbances to maintain normal operations (Hollnagel et al., 2006).

The Functional Resonance Analysis Method (FRAM) (Hollnagel, 2012), rooted in Resilience Engineering, is a recent approach designed to address the inherent complexity of STS. FRAM aims to understand processes in terms of functions and not components. A FRAM model focuses on interactions between activities and agents in the system and everyday performance adjustments that typically help keep things going right. In rare cases, the performance adjustments aggregate and propagate unexpectedly, leading to functional resonances, with accidents being the worst consequence. This approach helps to identify potential conflicts in the flow of interactions in complex systems.

In the past, FRAM has been widely used, applied, and enhanced methodologically in a variety of domains for retrospective as well as prospective analyses, as detailed in a comprehensive review by Patriarca et al. (2020). Hence, FRAM has progressively evolved since its starting point in 2004. The increasing interest in FRAM motivates the need for tools for performing FRAM analyses and expanding their capabilities. Four well-known examples of FRAM-related tools are: the FRAM Model Visualizer (FMV, Hill & Hollnagel, 2016), which helps build and graphically represent models and simulate dynamic and emergent system behavior with added metadata; the FRAM Model Interpreter (FMI, Hollnagel, 2020) integrated into FMV, which checks the syntactical and logical accuracy of FRAM models and ensures their consistency and completeness; myFRAM (Patriarca et al., 2017b), which converts FRAM models into tabular matrices for further quantitative or numerical analysis; and DynaFRAM (Salehi et al., 2021a), which captures both qualitative and quantitative variability, as well as temporal variations. These tools aid in modeling, simulation, visualization, and interpretation of system variabilities. However, they often lack a user-friendly interface for effective practical analysis and evaluation of a FRAM model’s characteristics.

This aligns with the current research-practice gap where systemic methods are not widely used in practice despite the recognized limitations of traditional methods (e.g., Read et al., 2013). Underwood and Waterson (2013) found that practitioners often face workload demands and perceive systemic methods as time-consuming and requiring extensive training. Steele and Paries (2006) reported that practitioners prefer straightforward methods with clear guidance to support analysis. The research-practice gap may be more evident with Safety-II methods like FRAM. Steele and Paries (2006) suggested that theories and models grounded in resilience engineering should be tailored for industrial use, facilitating their practical application and thereby bridging the gap between academically sound and practically viable methods.

A frequently mentioned issue is that FRAM suffers from the lack of quantifying normal and abnormal variability (Anvarifar et al., 2017; Patriarca et al., 2017c). This is inevitable as business or safety cases are often supported by any type of numbers because management is not interested in anything qualitative but rather in making their decisions based on quantitative outputs (Farooqi et al., 2022). According to Sujan et al. (2023), this issue is exacerbated when facing large-scale FRAM models where the number of functions and their couplings can quickly become overwhelming in the form of “spaghetti models”, and it is increasingly challenging to only use the graphical and qualitative representation of FRAM models meaningfully for analytical purposes and communication with stakeholders.

This combines with another challenge: FRAM lacks a structured procedure for determining recommendations and specifying safety interventions (Salehi et al., 2021b). The outcomes of some studies confirmed that it is challenging to employ FRAM to propose safety constraints in practice (Herrera & Woltjer, 2010). Therefore, to promote the adoption and usability of FRAM across various domains and industries, research should focus on developing user-friendly and accessible software tools and interfaces for conducting FRAM analyses as well as facilitating the visualization and interpretation of system variabilities to empower practitioners and decision-makers to use FRAM effectively in practice (Kumar et al., 2024). Nevertheless, it is crucial to keep the spirit of FRAM meaningful by preventing it from falling back into the traps of reductionism when integrating any type of quantification. Sujan et al. (2023) suggest providing a standardized report delivering basic evaluations in the spirit of FRAM, which would facilitate the communication between decision-makers and the modelers and analysts by telling a reasonable and useful "system story" through the lens of FRAM.

The FMV and myFRAM offer a form of quantification by providing data in a numerical format. However, there is no standardized evaluation and visualization of the results to guide the interpretation. At present, it is still all self-customizing, i.e., everyone builds their own evaluations and visualizations based on the numerical format, which is inefficient and also ensures little comparability. Therefore, in this paper, we present FRAMalyse, a novel software application, explaining how it supports an efficient and systematic analysis, visualization, and interpretation of system variabilities in a FRAM model or instantiation in a quantitative and user-friendly way.

2. Basics of FRAM

FRAM is based on four principles (equivalence of success and failure, approximate adjustments, emergence, and functional resonance) and follows four steps (modeling the system by identifying its functions, identifying the performance variability of the functions, aggregating the variability, and managing the variability). In the first step, the essential functions of a system are identified to construct a model. Each function is characterized by six key aspects – input, output, precondition, resource, control, and time – which couple each function to several others, forming a specific instantiation of the model typically represented graphically as hexagons. It should be emphasized that a FRAM model describes a system's functions with its potential couplings in general whereas an instantiation represents a 'map' of how a set of functions are actually coupled under given conditions. The second step involves specifying the performance variability of each function, which can be described using two phenotypes: timing and precision. In the third step, this variability is aggregated to examine how it propagates through the system, identifying where functional resonance occurs and leads to adverse outcomes. This is achieved by defining upstream-downstream relationships, where variability in upstream functions, such as changes in outputs that serve as inputs or resources, affects the variability of downstream functions. The fourth and final step focuses on monitoring and managing the identified performance variability to ensure the system's safety and performance. More details concerning the theoretical background can be found in Hollnagel (2012).

In epistemological terms, FRAM offers analysts a flexible tool comprising two main paradigms (Sujan et al., 2023). It can be used from a realist perspective (computational FRAM) to model systems and variability in a reasonably objective and potentially quantifiable way for prediction and evaluation or from a phenomenological perspective (reflexive FRAM) to gain an improved system understanding that underlies the functional interactions between system elements by telling different "stories" synthesizing a diverse set of knowledge, experiences, and interpretations. FRAMalyse mainly draws upon the realist perspective, trying to enhance the computational capabilities of FRAM.

3. FRAMalyse: analyse and evaluate a FRAM model

The purpose of FRAMalyse consists of supporting the analysis of steps three and four in FRAM, i.e., aggregating variability to identify functional resonance and managing the variability to ensure the system's safety and performance.

3.1. *General functionalities*

FRAMalyse is developed by Matlab App Designer as a free Standalone Desktop version for Windows environments. It is interfaced with FMV by importing the required FRAM model data in the form of Excel files. More specifically, FRAMalyse allows:

- Defining, editing, searching, and sorting functions in a tabular way with a detailed description of function type, agent, abstraction level/stage, and variability
- Calculating quantitative metrics representing variability, interaction, and complexity of functions and couplings
- Calculating Monte-Carlo simulation to identify critical paths of variable couplings
- Representing the FRAM model instantiation as a network in a grid assigned to agents and abstraction/space-time levels enriched by upstream and downstream functions information
- Assessing and visualizing model characteristics, interrelationships, and frequencies of network parameters
- Defining risk functions and visualizing the global system variability (GSV) and risk distribution over agent and abstraction levels and function types
- Assigning and visualizing risk functions along interaction and variability in a Functional Variability System Resonance Matrix (FVSRM)
- Importing model and instantiation data and exporting tables and images

More details and examples enriched by visualizations can be found in a user guide along with the release of FRAMalyse.

3.2. Parameterization and Calculation

Initially, new model data or an existing instantiation consisting of calculated metrics has to be uploaded. Afterward, several parameters can be defined and used to calculate a bunch of metrics.

3.2.1. *Parameterization – Function type, agents, stages, and variability manifestation*

First, the functions are defined in a tabular way, enabling a further detailed description by assigning customizable agents, stages, and function types (color-coded) and defining variability manifestation in terms of timing and precision by percentual frequency (see Fig. 1). In addition, the order of agents and stages can be determined for the visualization of the network in a grid, as detailed in Section 3.3.1. It is also possible to generate test data.

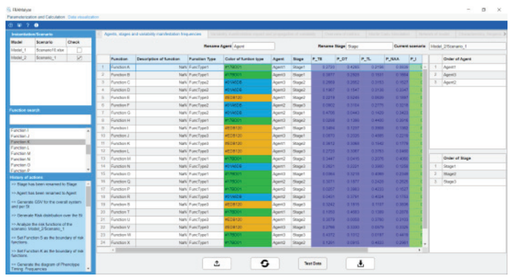

Fig. 1. Overview of function parameterization regarding agents, stages, function types, and variability manifestation.

3.2.2. *Parameterization – Variability impact and propagation*

Once the basic data of the functions are defined, the user can set and assign the numerical parameters of variability manifestation, propagation of variability, and weighting factors for specific metrics calculated in the next step. The variability of the upstream output is assigned a score in terms of timing and precision, e.g., the higher the score, the more variable the output. The propagation of variability is expressed by an amplifying, no or damping effect. The weighting factors are used to calculate the weight of a function as an upstream and downstream function, according to Grabbe et al. (2022). It should be emphasized that all numerical values are customizable.

3.2.3. *Calculating metrics*

Finally, several metrics can be calculated following the quantitative approach by Grabbe et al. (2022). Note that the complete definitions and equations can be found in the aforementioned work. The metrics can generally be divided into three categories: functional variability, system resonance, and system propagational variability. Functional variability represents the variability that a function directly receives and transfers without considering their interaction and effect in the system sufficiently. Therefore, the system resonance tries to reflect the interaction and complexity of a function, incorporating the system's non-linearity, emergence, and dynamic. It is a kind of weighting of the impact and affectedness of a function to evaluate the effect of a function variability system-wide. Combining functional variability and system resonance results in system propagational variability, which shows the systemwide impact and affectedness of each function's variability up to a GSV level. After the calculation, the metrics are assigned to each function and coupling tabularly.

3.2.4. *Monte-Carlo Simulation*

Lastly, a Monte-Carlo simulation can be implemented to identify critical paths of variable couplings. It can be chosen between two options: all paths or shortest paths. Also, different settings can be defined: the number of runs, the error probability, a threshold from which the value of the coupling variability (CV) is critical, and the longest paths considered. For evaluation, two tables are provided. One table lists all upstream-downstream coupling combinations between three functions, showing the frequency of how many times the CV of all related couplings exceeds the criticality threshold. Combinations that exceed the set error probability are marked red; the rest are green. The second table lists the longest critical paths, detailed by the frequency of criticality. Moreover, it is possible to compare different instantiations.

3.3. Data visualization

Once the metrics are calculated, the data is visualized for a structured analysis and evaluation.

3.3.1. *Descriptive information*

First, descriptive information is given, distinguishing between three categories:

- Network of model
- Characteristics, frequencies, and interrelationships
- Interdependencies – Chord diagram

The network represents the FRAM model instantiation in a grid assigned to agents and abstraction levels, which aligns with the Abstraction/Agency framework by Patriarca et al. (2017a), enriched by upstream and downstream functions information (see Fig. 2).

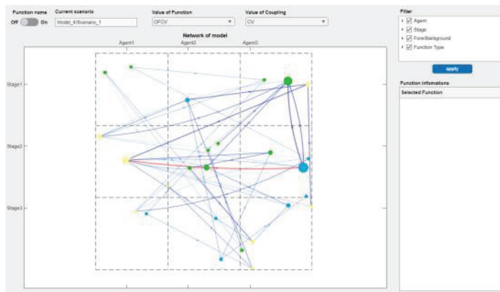

Fig. 2. Visualization of an instantiation of a FRAM model as a network in a grid assigned to agents and stages.

Here, nodes represent functions with a node color indicating the function type and the node size representing the value of a selected metric. Directed edges represent couplings, with the color intensity representing the value of the selected metric. When selecting a function, all upstream (orange) and downstream (blue) couplings and their respective functions are displayed. In addition, it is possible to depict the critical paths identified by the Monte-Carlo simulation. Besides, a filter can be used based on the agent, stage, function type and foreground/background function.

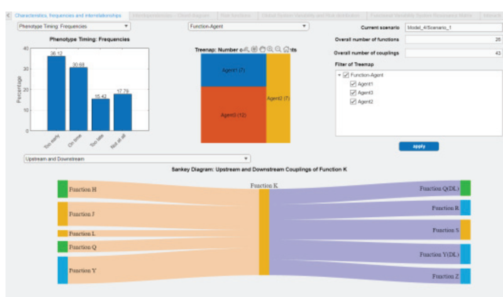

Fig. 3. Visualization of model characteristics, interrelationships, and frequencies of network parameters.

Several figures illustrate the characteristics and frequencies of network parameters for a selected function or the whole model (see Fig. 3). A histogram shows the values of chosen parameters, such as the frequency distribution of variability in terms of timing and precision. A treemap depicts the number of functions and couplings within and between agents, stages, function types, and aspects. A Sankey diagram outlines a selected function's upstream and downstream couplings as quantity flows, visualizing the CV's proportion by the respective flows' size. Additionally, the number of functions and couplings of the entire model is displayed.

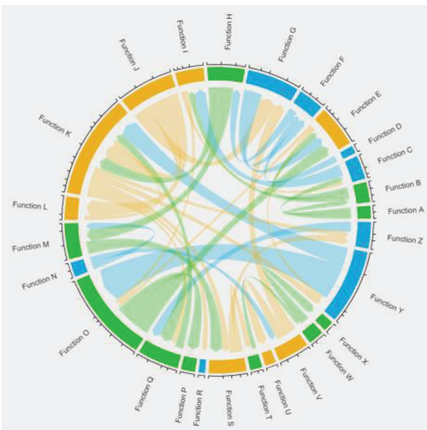

Fig. 4. A chord diagram visualizes the connectedness between functions.

The interdependencies between functions are depicted by a chord diagram radially showing the couplings between all functions (see Fig. 4). This figure enhances the network representation by an improved visualization of the connectedness between functions.

3.3.2. *Evaluation*

Second, an advanced evaluation enables the identification of risk or critical functions. Functions are prioritized and ranked using the scree test based on a chosen metric. Subsequently, risk functions can be graphically defined and used for further analysis. Here, the GSV and risk distribution over agent, stage, and function types are depicted on a broader global level, including all functions or the selected risk functions. The diagrams can also be used to compare different instantiations.

Furthermore, all functions are assigned along interaction and variability in the FVSRM (see Fig. 5), according to Grabbe et al. (2022), to represent the criticality of functions and their potential for functional resonance, which offers a fine-grain level analysis regarding the individual functions. The lower and upper boundary values of each dimension are customizable. Also, each area is clickable, providing a list of the related functions.

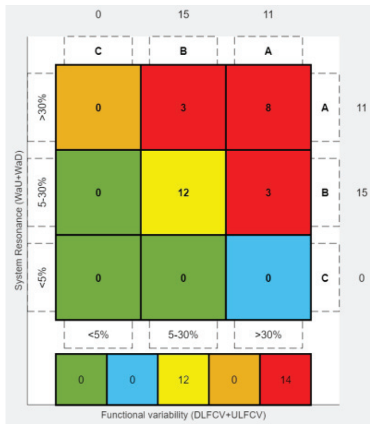

Fig. 5. The Functional Variability-System Resonance Matrix (FVSRM).

Based on the FVSRM, the selected risk functions are visualized along functional variability and system resonance, differentiating between the upstream and downstream shares in a stacked way (see Fig. 6). These figures can also be used to compare risk functions between different instantiations.

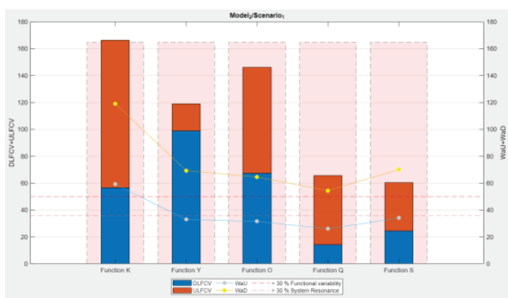

Fig. 6. Overview of risk functions along functional variability (stacked column) and system resonance (stacked lines).

3.4. Application purposes

FRAMalyse can be applied for a wide variety of purposes. First, it facilitates the comprehension of the characteristics of a FRAM model or its instantiation to get a holistic overview by providing standardized descriptive information. Second, it supports the analysis of variability, centrality, and couplings to identify spots of functional resonance and adaptive capacity, or critical paths, which can be used as leverage points to intervene in the system. Third, it enables the comparison of different scenarios in terms of what-if analysis or differences between work-as-done and work-as-imagined. This can be done globally regarding the entire system or subparts or on a fine-grain level regarding individual functions. Also, it offers the possibility to identify interaction patterns that recurrently occur over several instantiations. A typical application example could be the comparison between humans and automation, as utilized by Grabbe et al. (2022) and Grabbe (2024) in the driving context.

4. Discussion

FRAMalyse is a tool designed to solve practical problems that FRAM analysts encounter every day, such as facilitating the efficient and structured analysis and interpretation as well as communication of results to the management. It strengthens the computational capabilities of FRAM, which makes the FRAM more actionable for real-world purposes, particularly when facing large-scale systems.

At the moment, FRAMalyse treats a FRAM model or instantiation only as a static process like a snapshot, which means that dynamics and feedback loops in the form of behavioral changes over time are not addressed. Dynamics are only partially incorporated by automatically generating multiple instantiations of the same model through Monte Carlo simulation to compare critical paths of couplings. This aspect of dynamic simulation can be more effectively addressed in FMV through the use of metadata functionality, as introduced by Hill and Slater (2024). However, there is a lack of comprehensive visualization of real-time data.

The current version of FRAMalyse has already undergone alpha-testing with peers, which helped evaluate its initial value and ease of use. In the near future, a beta-test with international safety and FRAM experts will be conducted to explore additional potential features and approaches, with the goal of refining interfaces and enhancing the user experience. Additionally, it is essential to examine how the quantitative approach avoids falling into reductionist mathematical assumptions while remaining valuable for management decision-making, all while maintaining a systems-thinking perspective consistent with FRAM's principles. Striking a balanced and nuanced approach between pragmatic simplification and idealistic complexity is crucial.

Furthermore, when FRAMalyse is made publicly available, we plan to conduct empirical evaluation surveys to assess its usage, identify strengths and weaknesses, and enhance its effectiveness and functionality. We are confident that FRAMalyse will support and amplify the potential of FRAM analysis, promoting its application among researchers and practitioners. This represents an important step toward establishing a foundational platform, integrated with FMV, to facilitate FRAM’s practical and actionable application across various socio-technical systems, guiding analysis, interpretation, and communication in real-world settings.

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