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ORIGINAL ARTICLE

Unveil key functions in socio-technical systems: mapping FRAM into a multilayer network

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Abstract
Network theory has been widely used to describe many complex systems belonging to several fields from physics to sociology. Particularly interesting are multilayer networks which concurrently account for several types of relationships, without necessarily aggregating them. The functional resonance analysis method (FRAM) is an agnostic method (i.e., not making modeling assumptions) allowing semantically rich descriptions of the relationships among functions constituting a socio-technical system. This richness may soon become overwhelming in case of not trivial FRAM models. A multilayer network represents a promising choice for combining the long-proven experience in network theory with the FRAM's agnosticism. On these observations, this article shows how a FRAM model can be reinterpreted as a five-layer multilayer-directed network without any loss of information, even reducing the cognitive workload required for the analysts. This paper defines a methodology able to prioritize potentially critical functions through dedicated network centrality descriptors, and to generate instantiations for comparison and benchmarking of scenario-based envisioned solutions. A walk-through application in industrial operations management confirms the feasibility and validity of the proposed methodology.

Keywords Organizational dissonance · Decision making · Complex networks · Industrial operations · Resilience engineering · Safety-II

1 Introduction

Complex systems are systems with peculiar features such as non-linearity, emergency, and self-adaptation among others, and whose behavior is inherently difficult to model. This difficulty arises from the high number of relationships of various nature existing both between the different parts of the system and with the environment that delimits the system itself (Gros 2015). On one hand, its behavior is what produces the complex features (emergency, non-linearity, self-organization, adaptation and others). On the other hand, these characteristics govern entirely, or almost entirely, the system's behavior in a circular way.

This intertwined mechanism makes systems behaviors not simply subtended by the properties of complexity. Any modeling approach that ignores this issue or characterizes it as marginal will produce inaccurate and, above all, useless models. A frequent solution is to use a network, represented as a graph, to describe the interacting components of a complex system. Network theory proved to be well suited to investigate some emergent non-linear characteristics difficult to express otherwise, (e.g.) cascading failures, behavioral synchronicity, epidemics propagation and resilience to external attacks. Graph theory is applied to complex networks since it is supported by many algorithms, techniques, heuristics and metrics already available which have been proven to succeed in describing many features of complexity. So far, no unique theory of complex systems has emerged, thus researchers solve specific problems case by case.

Complex systems of particular interest are the so-called socio-technical systems, in which people, technological and social elements interact for a specific purpose, dealing with several contrasting goals such as efficiency, thrift and safety, in a self-adaptive way (Franssen et al. 2014). For example, a modern industrial plant involves different stakeholders (both individual and collective), and machines and software subsystems. Stakeholders and technological subsystems might be related at a process, directive, regulation, control level or

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just following a generic interaction. These multiple interactions, mostly non-linear and transient, mean that unwanted outcomes can occur even though the plant goes through a normal state (i.e., not a failure scenario). Accidents are not caused by failures, but they can possibly emerge during ordinary working performance.

About safety management, resilience engineering (RE) is that paradigm which maintains the focus on system complexity. For RE, failures, accidents and damage are emerging phenomena from the entire system's behavior, therefore, cannot be simply identified at the level of sub-components. Complementarily, resilience is the emerging property of a complex system to adjust its operation prior to, during and after disruptive events, to support the operations required under any condition (Woods et al. 2006). Resilience engineering in the last decade has started to acquire more and more interest in different application fields, also because of its naturalistic dimension, oriented to the processes as they happen in reality (Work-As-Done, rather than Work-As-Imagined).

The functional resonance analysis method (FRAM) is a method to model socio-technical systems, used mostly within RE. It presents several advantages, namely: it allows characterizing systems through a rich description of the relationships at a functional level, and it is a sine model method, allowing thus a description of the system in its normal operating circumstances, without limited modeling assumptions and post hoc fallacies (Hollnagel 2012a). The FRAM method is up to now essentially qualitative, except for the enrichment and evolution proposed by some authors (Bellini et al. 2016; Patriarca et al. 2017c; Rosa et al. 2017).

Starting from this exploratory line of research, this paper suggests a transposition of the FRAM—without loss of information content—into the language of network theory, with the aim of exploiting the best of the possibilities offered by both: the agnostic modeling of the FRAM and the tried and tested methodologies of the network theory.

This article aims to propose a methodological contribution to answer the following research questions: "Is it possible to transpose a FRAM model into a network without losing information content?" and, in case, "How should a methodology be designed for instantiations comparisons relying on network theory?". Such questions would be answered adopting a design science perspective (Simon 1996), including testing and validation by means of a walk-through application in industrial operations.

The remainder of the article is organized as follows. Section 2 outlines some of the aspects of FRAM relevant for the purpose of this research. Section 3 describes the proposed methodology, based on multilayer networks, then contextualized in the context of industrial operations (Sect. 4). Finally, the conclusions summarize the obtained results and the advantages of the proposed approach, also hypothesizing potential future developments.

2 Some details on the FRAM

This section provides a brief bird's-eye description of the FRAM, neglecting to describe the process in the consecutive steps in which the method is divided, as is usually done in reviewing the method. The interested reader will find more than exhaustive descriptions in Hollnagel (2012b). The aim of this unusual approach is to capture the essence of the method by highlighting some distinguishing aspects less recurrent in literature.

The FRAM, in a completely agnostic way, prescribes a sequence of steps that lead to the generation of descriptive knowledge of a system or a part thereof (Johannesson and Perjons 2014), as a list of elements (called hexagons, snowflakes or, more properly, functions). This set of key functions is what constitutes the FRAM model (Fig. 1).

Certainly, the actual system, which is approximated by the model, is much more complex than a single instantiation: firstly, because the length and depth of the list of functions in which the model is translated depend on who implements the method; secondly because the system emerges precisely from the interaction of these functions; in lay terms, the whole is greater than the parts. The first limit is inherent with the finiteness (cognitive and situational) of the observer and is inseparable from the modeling activity. The second is overcome by the method—at least from a theoretical point of view—by introducing the concept of instantiation (Patriarca and Bergström 2017; Patriarca et al. 2018b). The instantiation process is the way the method translates the relational organization between functions in terms of sequence (upstream–downstream coupling) and type of relationship (Output–input[1] coupling) that might occur in a different way each time (Hollnagel 2012b).

It is possible to distinguish between two forms of instantiations: emergent and calculated (Hollnagel 2016). The conditions in which the system operates determine the state in which each function of the model comes across which, in turn determines:

- if verified, the conditions that guarantee the existence of a coupling between one of the five minor inputs of a function and the Output of a function upstream,
- if the Output of the function upstream triggers the activation of the function downstream and, if so, the value of its Output.

[1] An input is considered as any input, i.e., Input, Precondition, Resource, Control, Time.

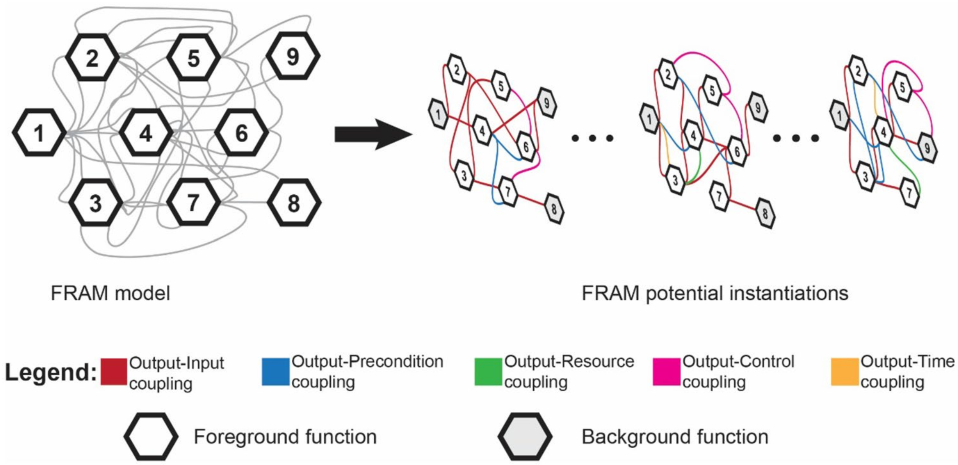

Fig. 1 The functions listed by the analyst represent the FRAM model, to which corresponds a certain amount of potential realizable instantiations. In ordinary conditions, the system goes through only a few of these potential instantiations, but with the same mechanism, sometimes it can pass through a state corresponding to an unwanted instantiation. Instant by instant, the system with its behavior activates some functions forming continuous, transient and different—in type and order—couplings among the activated functions. This process is continuous, unstoppable and unbounded, but we make the analysis actionable by stemming it to some foreground functions

Thus, the instantiation that comes to realize is itself the cause of the connections that constitute it: it emerges. The (emerging) instantiations are another example of those complex characteristics mentioned in the introductory section.

Otherwise, if we make the hypothesis of knowing the sequence in which the functions are related, then the instantiation realized becomes a static object whose boundaries are well determined. An instantiation of this type can be interpreted as a network whose nodes are the functions and the arcs are the achieved couplings. This is a practical solution to account for the quantitative aspects of RE: in this way the instantiations can be calculated, as long as in the calculation is given account of the unpredictability of the system analyzed.

The notion of instantiation is another advantage of the method because it allows the recoding of embodied (resident in individuals) and embedded (resident in technological and social entities) knowledge into explicit knowledge (in the model and its achievements) (Hedberg 1981; Madhavan and Grover 1998; Lam 2000). In this regard, a typical use of FRAM refers to modeling instantiations corresponding to the body of norms and prescriptions of the socio-technical system (Work-As-Imagined), to be compared with instantiations that are realized in practice (Work-As-Done). Comparing different scenarios through the corresponding instantiations is an additional possibility allowed by the analyses conducted through the FRAM (Ferreira and Cañas 2019).

3 Multilayer network representation of the FRAM instantiations

It has been acknowledged that the FRAM is not a network, nor a flow, but only the systematic description of the key functions of a system, with connections that are not stable but transient expression of functional interdependencies that can change accordingly with the operating conditions (Hollnagel 2012b).

However, it would be argued that the transience of the links and the decomposition of the system in functional—rather than structural terms—do not prevent its description in terms of network, since a network may be abstract and time dependent. For a system to be described in terms of a network, it is sufficient that there are relationships of some nature between its elements. There are word networks (Zuo et al. 2016), citation networks (Wears 2017) and functional brain activation networks (De Domenico 2017). The Bayesian networks themselves are direct acyclic graphs (DAGs) in which some variables are linked through their conditioned probabilities.

With regard to time, in general, each network can be thought transient in some sense, for example the networks of biochemical processes are extremely time dependent. In those networks, protein complexes act as intermediate products (i.e. as broker nodes, for other nodes) continuously forming and disappearing (Yu et al. 2008).

It is worth specifying that a network is a graph with semantics—established by the observer himself—that with his point of view delimits what we mean by system. The very concept of resilience has been immediately interpreted in the context of networks, in which a graph is all the more resilient, as it is capable of ensuring service at increasing percentages of nodes and/or missing links (Lü et al. 2016; Newman 2018).

3.1 Previous attempts to describe FRAM as a network

Some authors have plainly compared FRAM to the science of networks before the present work. For example, the sociological actor–network theory (ANT), strongly centered on the concept of network and relations, has been used in communion with FRAM as a methodology for understanding terrorist phenomena (Masys 2018). In this application, the radicalization has been contextualized as the translation process of ANT (i.e., problematization, interessement, enrollment and mobilization). The performance and effectiveness of the translation phases were described in terms of functions necessary to carry out the activity of radicalization, through a simple FRAM model. Such initial modeling attempt described the network of relationships among actors (i.e., indifferently humans, social and technological artifacts, as well).

Rosa et al. (2015) proposed using FRAM in connection with the analytic hierarchy process, a structured technique for complex decisions grounded in graph theory. FRAM was compared with Bayesian networks and fault trees in investigating a feeding control system transferring propane from a propane evaporator to a scrubbing column (Smith et al. 2017). The study at the time showed the FRAM's great depth of analysis, but also the limit due to its non-quantifiability.

Similarly, as abstract networks, a clever approach, potentially very fruitful, has been recently used. It consists in modeling the FRAM instantiations with timed automata networks and, through formal verification, in analyzing their behavior based on rules of variability. Functional resonance can be automatically demonstrated by the generation of emerging instantiations and opportune countermeasures can be developed by damping resonance; in addition, the effectiveness of these countermeasures can be verified with the same methodology (Duan et al. 2015; Zheng et al. 2016; Tian et al. 2016; Yang et al. 2017).

As for a more explicit use of network theory in its different meanings, Lee and Chung (2018) defined a particular type of heterogeneous network (i.e., whose nodes are of different types) called Human–System Interaction (HSI) network, equipped with nodes function and node agent. The nodes can be connected with five types of abstract relations in total. This taxonomy allows for a complementary classification of variability.

In systems, variability propagates cascading in a process of incremental fragmentation or coalescence. It can be operationally detected at the function's Output, through a typical network centrality index, the out-degree (here called reverberation) which has been used in junction with FRAM couplings' criticality to build a matrix offering a functional prioritization of their impact on the system (Patriarca et al. 2018b). Lundberg and Woltjer (2013) proposed a representation of the FRAM by constructing a matrix connecting the individual functions called Resilience Analysis Matrix (RAM). The RAM corresponds to the adjacency matrix of the aggregate graph obtained from the corresponding calculated instantiation. The article is useful in showing how it is possible to identify some characteristics starting from visual patterns in the matrix layout. These patterns are similarly described in matrices obtained from systems, but with non-oriented relationships (Eppinger and Browning 2012). Patriarca et al. (2017b) have given nourishment to RAM, redefining it from the couplings and not from the functions, allowing to build on it an algorithm for searching the upstream functions. In terms of graph theory, this second matricial encoding corresponds to the matrix of adjacency obtained from the transformation of the graph in a line graph, i.e., the graph built by replacing new nodes to the existing arcs, and arcs (lines) instead of the old nodes. It can be demonstrated that the same search can be carried out with a different algorithm based on power of the adjacency matrix of the starting graph; the two descriptions are in fact equivalent in substance (Saberian et al. 2014).

Bellini et al. (2017) proposed the most explicit attempt in the context of the resilience of the urban transport system. This research emphasizes the human-oriented readability of traditional FRAM and points out that its translation into the language of networks would provide support for quantitative analysis. The authors encoded FRAM as a bipartite network (i.e., a network in which input and Output nodes belong to disjointed sets), weighing the links after interviews and workshops with interested stakeholders. The authors also used some network analysis metrics such as closeness and betweenness centrality. They observed that the identified centrality indices were not representative of the characteristics of FRAM, since in their case study also the peripheral nodes were important. This is probably because centrality is not an absolute concept in network theory, but depends on the criterion chosen. There are many different indexes of centrality and the most appropriate should be identified case by case (Borgatti 2005). Furthermore, Bellini et al. (2017) proposed an interesting fuzzy approach to the quantification of variability.

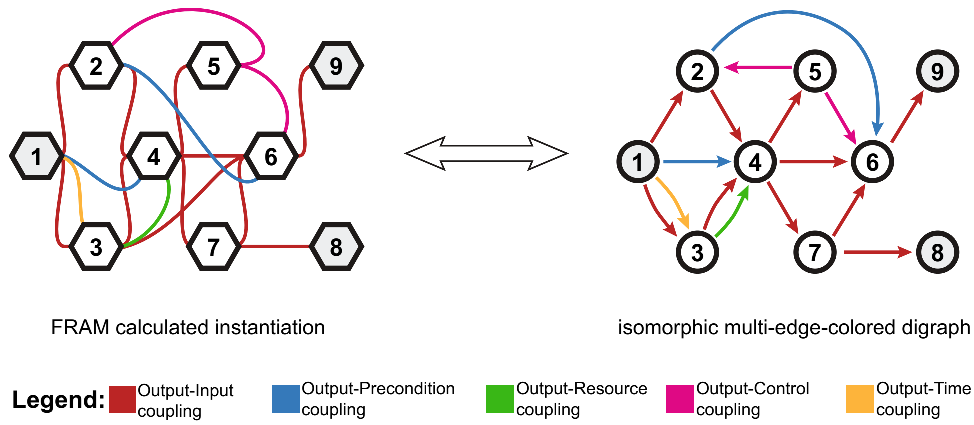

Fig. 2 A graph capable of maintaining the same semantic richness of a FRAM instantiation should be a digraph (to keep the information about the upstream–downstream coupling); a multigraph (because more links between the same nodes are allowed) and an edge-colored graph (to keep the information about the Output–input coupling)

3.2 The five-layer multilayer network framework

It has been previously stated that a calculated instantiation can be represented with a network by associating a node to each function and an arc to each coupling. However, such representation is equivalent to a simple graph or, at most, a simple digraph, if the order relationship between functions achieved in the instantiation process is maintained. In these cases, the proposed graphs are not rich enough to fully represent FRAM instantiations. In fact, such a network would take into account the upstream–downstream coupling, but not the Output–input coupling (i.e., the type of connection), and in FRAM the types of coupling that can be actualized in an instantiation are five: Output–Input, Output–Precondition, Output–Resource, Output–Control, Output–Time.

According to Douglas Hofstadter (Hofstadter 1999):

> The word "isomorphism" applies when two complex structures can be mapped onto each other, in such a way that to each part of one structure there is a corresponding part in the other structure, where "corresponding" means that the two parts play similar roles in their respective structures.

Following the previous definition, a graph isomorphic to a FRAM instantiation should be a multi-edge-colored digraph (Fig. 2).

An important and promising approach to network analysis is multilayer networks, allowing descriptions of complex systems without disregarding the different informative nuances of relationships (Bródka and Kazienko 2014; Kivelä et al. 2014). A multilayer network consists of several coexisting standard networks, each capable of encoding an information aspect of a system. Ordinary networks can be represented algebraically by adjacent matrices, indicating in a compact way the presence, direction and intensity of the connections between the nodes of a network. Multilayer networks need tensors to be represented. Tensors are structures that generalize the concept of matrices (a matrix is a tensor of rank 2, i.e., a tensor with two dimensions—rows and columns). In general, the components of the multilayer adjacency tensor of N nodes and L layers are indicated with $M_{j\beta}^{i\alpha}$ and condense the information related to the existing connectivity between the element i in layer α, and the element j in layer β, with $i, j = 1, 2, \ldots, N$ (De Domenico et al. 2014).

The operation transforming the adjacency tensor into an $N \times L$ supra-adjacency matrix is called "flattening"; this supra-adjacency matrix has a block structure where the blocks on the diagonal encode the intra-layer connectivity and the off-diagonal blocks encode the inter-layer connectivity. Multiplexes are multilayer networks where the same node is replicated on more than one layer, where it exhibits its inclusion in the concept of connectivity expressed by that layer. A multiplex topology is a multigraph (more than one link between the same nodes is allowed) edge-colored (each edge communicates a distinct size) in which the only inter-layer links allowed are those between replicas of the same node (Horvat and Zweig 2014). Therefore, a calculated instantiation of a FRAM model can be represented as a five-layer multiplex network, which does not represent a multilayer abstraction representation (Patriarca et al. 2017a). Figures 3 and 4 show, respectively, the multilayer network isomorphic to the calculated instantiation from Fig. 2 and the supra-adjacency matrix resulting by flattening its adjacency tensor. Often for calculation reasons, an equivalent representation is preferred in which there are replicas of each node in all layers, some of which are simple placeholders, and all replicas of the same node are held together by a clique (a complete graph).

3.3 Integrating FRAM with multilayer network framework

This section describes the methodological approach for integrating FRAM with multilayer networks described in Sect. 3.2. This approach includes some standard FRAM

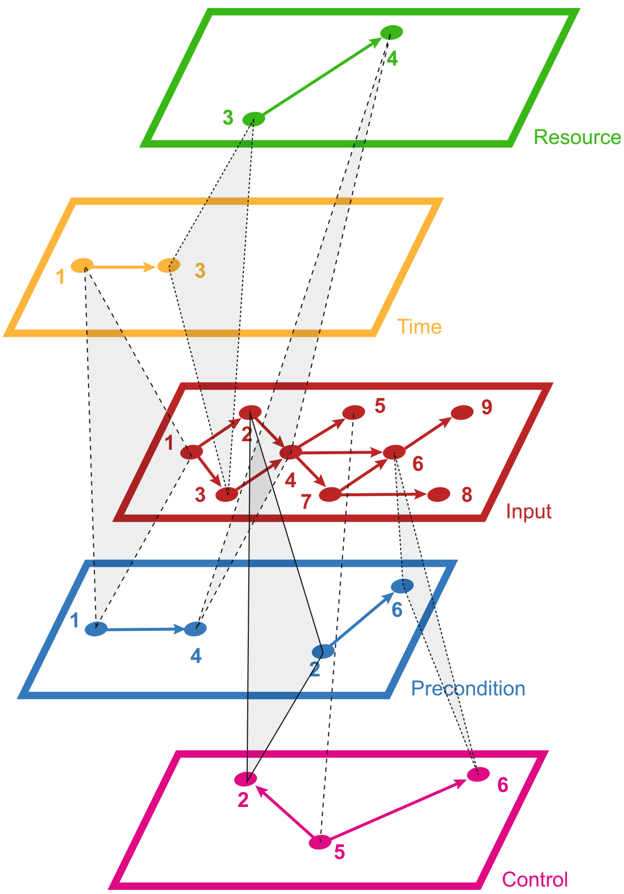

Fig. 3 The multilayer network isomorphic to the multi-edge-colored digraph, which in turn corresponds to the calculated instantiation from Fig. 2; Each layer supports a digraph which encodes the information corresponding to the specific Output-input coupling relationship. The consistency of the topology is ensured by the (bi-directional) interlayer links between the different replicas of the same node (function) in the five layers. The triadic relationships are here depicted only with the purpose of visual clarity

building steps, and additional ones, conceived as part of a joint iterative procedure.

- *FRAM step 1* This step is aligned with traditional FRAM theory and it is aimed at generating a list of functions and associated descriptions for a specific system under investigation (Hollnagel 2012b).
- *FRAM step 2* This step is aligned with traditional FRAM theory and it is aimed at identifying the variability of functions defined in FRAM step 1. In this phase, the functions are described by means of all their relevant aspects (Hollnagel 2012b).
- *FRAM step 3* This step starts from traditional FRAM theory, but it is here enhanced through a semi-quantitative framework based on Monte Carlo simulation. The variability scores obtained at the end of the simulation can be interpreted (in a network perspective) as weights of the arcs, which represent the FRAM couplings (Patriarca et al. 2017c)
- *Multilayered network* This step is the first pragmatical consequence of network theory as applied to FRAM. The aim of this step is the generation of a tensor able to translate the FRAM model into a multilayer network, without losing any information. The transformation is conceptually grounded on the concepts presented in Sect. 3.2.
- *Functional prioritization* This step further expands the network analysis developed through the tensorial representation. In particular, in this phase, it is possible to adopt a network metric for the prioritization of functions. The metric adopted should reflect a centrality measure, which will be a combination of couplings' weights and couplings' connectivity. For this purpose, several metrics can be used, each one with a different scope. The most relevant ones are:

  - *Degree and strength* Degree accounts for the number of the neighbors owned by a node. If the network is directed (as for FRAM models), the measure can be split in two: *inDegree*, the number of incoming links; and *outDegree*, the number of outgoing links, already labeled as reverberation in previous studies (Patriarca et al. 2018b). Typically, one is interested in indegree, since inlinks are given by other nodes in the network, while outlinks are determined by the node itself. However, in case of FRAM transposition, it may be more interesting in outlinks because variability manifests itself at the Output of a function. *Strength* is the weighted version of degree and correspondently it can be decomposed into *strengthIn* and *strenghtOut*. Both degree and strength are representation of local properties (effects of immediate neighbors, i.e., nodes connected directly).
  - *Eigenvector centrality index* is a measure of the influence of a node in a network assigning the highest scores to nodes well connected with other high-scoring nodes, hence accounting for the whole network. In this sense, it differentiates from strength and degree, offering a wider perspective not limited to immediate neighbors.
  - *Hubs and authorities* In direct networks, it is possible to classify nodes according to their importance as emitters or receivers of connections, respectively. Nodes pointing to an important node generally point to other important nodes as well, building a structure roughly bipartite where the relevant nodes, *Authorities* are mostly pointed by special nodes called *hubs*. It follows that high-centrality authority nodes are linked by high-centrality hub nodes.
  - *PageRank centrality* When there is lack of knowledge of the full topology of a network and only local

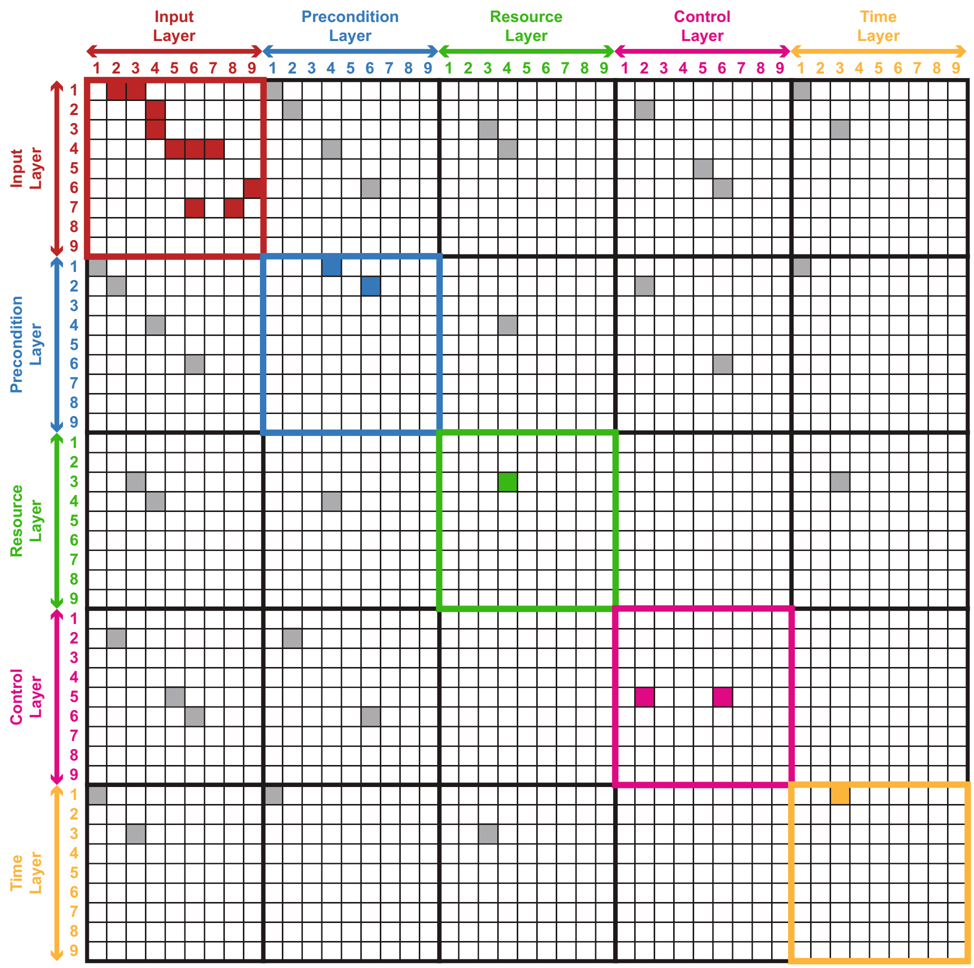

Fig. 4 The supra-adjacency matrix corresponding to the multilayer network of Fig. 3. It is a (NXL)X(NXL) square matrix. Each characteristic block is an NXN square matrix. Each block on the diagonal encodes the intralayer network of the corresponding layer. The off-diagonal blocks are symmetrical, because each of them encodes the interlayer (bi-directional) network between the corresponding layers

information is available, random walks can be used to calculate centrality. *PageRank* can be viewed as a stationary distribution of random walk on the network. However, this metric needs the couplings' weights to be a measure ordered and equally spaced. Note that a *Walk* is a sequence of edges, while a *Path* is a particular Walk, whose nodes are never taken twice.

- *Katz prestige* is a centrality index that considers prestigious a node with a large number of shortest paths to other nodes. The shortest path is the path whose length (the weighted sum of its edges) is the lowest among all the possible paths.

Katz prestige can be seen as a variant of Eigenvector: it penalizes the contributions of distant nodes and it may be a reasonable choice for complex system, whose measure of couplings weights does not satisfy the assumptions of PageRank.

Based on these observations, the most suitable metric to be used for function prioritization seems to be Katz centrality, called Katz hereinafter, considering that the weights coming from FRAM step 3 are not equally spaced (Patriarca et al. 2018b).

- *Experts validation* The results from functional prioritization has to be assessed and validated with the support of subject matter experts, who have experience in the work domain. It is recommended to involve people who work in the system at hand, and thus who can confirm the significance of the analytic results based on real-world experiences. Due to the type of analysis, and the need of having open discussions, it is recommended to develop focus groups (Patton 2002). In case of need, there could be the need of iterating some previous step (e.g.,) reconsidering potential biases or mistakes in one of the previous steps.
- *Instantiation building* Once a subset of function has been prioritized through the network analysis, and results have been validated, it is possible to develop a specific set of instantiations from the original FRAM model. In particular, besides a base instantiation constituted by the prioritized functions, it is possible to generate a set of n instantiations, which represent functional representa-

tions of different envisioned systems. Such instantiations are developed updating the base instantiation through the addition/substitution/modification of alternative functions, and variations to the original work domain, with the purpose of providing more effective and sustainable work domain solutions.

- *Tensorial representation of instantiations* This phase is aimed at the translation of the developed instantiations in their respective tensors. Tensor building is a preliminary phase for the subsequent metric analyses.
- *Tensorial representation of the FRAM model* Starting from the tensorial representation of each instantiation, this phase is aimed at the building of a tensorial representation of the corresponding FRAM model. This latter will be constituted by $(n + 1)$ instantiations, i.e., the base one, plus the alternative n instantiations. Note that this phase constitutes the central step for the subsequent metric analyses: it allows the development of a template to generalize comparisons among different instantiations. These latter are in principle represented by tensors of different dimensions (due to different number of functions, couplings, agents), since each one may have a different number of changes compared to the base instantiation. The notation "template" is here used to define a tensor whose size is $L \cdot \left(N + \sum_{i=1}^{n} f_i\right)$, where L is the number of layers (i.e., 5), N is the number of functions in the base instantiation, and f_i represents the functions added to the base instantiations for the development of instantiations i. Note that for the sake of comparison, it could be possible to define further instantiations as a combination of multiple previously developed instantiations, i.e., instantiations taking into account multiple changes contemporarily. For the subsequent analysis, those functions (and associated couplings) not present in a specific instantiation will be initialized with null values in the corresponding elements of the template tensor, still allowing systematic and holistic comparisons.
- *Benchmarking and experts validation* This phase is aimed at prioritizing the instantiations defined in the previous phases in order to define the most effective solutions. A benchmarking procedure is developed and validated with the support of experts. The benchmarking is based on two main dimensions, i.e., performance and feasibility. The former will be based on the assessment of network metrics for base and alternative instantiations, rewarding the ones with the most significant changes. Nevertheless, as a pragmatic application of the ETTO principle (Hollnagel 2009), each instantiation has to be assessed in terms of its feasibility. This latter could be assessed through the required investment cost, or even through more qualitative criteria (adequacy to current workforce, physical limitations, cultural resistance, etc.). It is important to note that the assessment has to be developed jointly with a pool of subject matter experts, possibly through a focus group.
- *Revised model* Once the selected systemic changes have been selected (and possibly implemented), a new model is required to further iterate the process, in a continuous improvement perspective.

This iterative methodological approach is depicted in Fig. 5, which summarizes each phase and their conceptual roots (traditional FRAM, semi-quantified FRAM, multilayered FRAM).

4 Walk-through application

This section details the application phases of the proposed approach through a walk-through application in an industrial plant. Besides a background section, each section provides operational description of the phase application.

4.1 Background on the work domain

A power-tool accessory production plant provides a suitable study context to evaluate the multilayer network approach to FRAM modeling. Starting from a few semi-finished products, the company produces a wide range of finished products, even though approximately three types of semi-finished products correspond to three families of final products (Fig. 6). The management of the company perceived the forging activity, especially that related to the first family of products, as safety—critical for the plant, by virtue of the number of accidents in which it was involved. At the beginning of the work shift, the operator starts by carrying out a standardized check, which should lead to a free and well-organized and, above all, safe work area.

Afterward, the operator checks both oil and cooling water refiner levels as much as checking the full functionality of collective and individual barriers. The same worker also checks the correctness of the machine's setup required to manufacture the needed items. Only if all the previous checks provide positive results, the operator has clearance to load and start the forging machine. At the beginning of each cycle, the worker unloads the products, after checking their quality, and loads the machine with new raw materials. Once the planned set of pieces is manufactured, the forging operator replaces the molds according to the next scheduled item. In case of technical issues, the worker must contact the maintenance team by a phone call. Besides the former operator activities, the focus of the present work has been addressed to the amount of the auxiliary actions related with the forging, to those actions related with safety management and finally to the activities pertaining machine's design and maintenance.

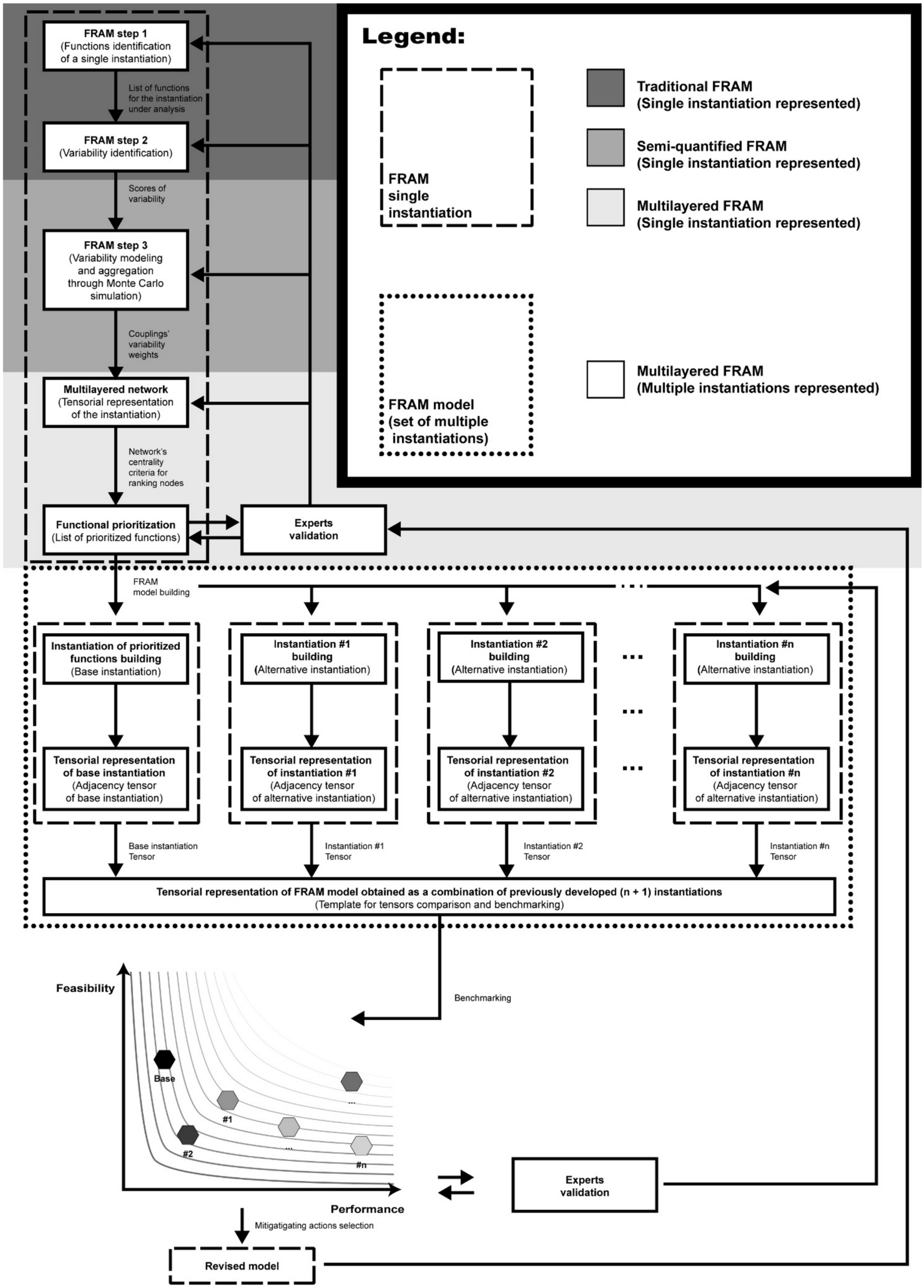

Fig. 5 Methodological phases of the proposed integrated approach

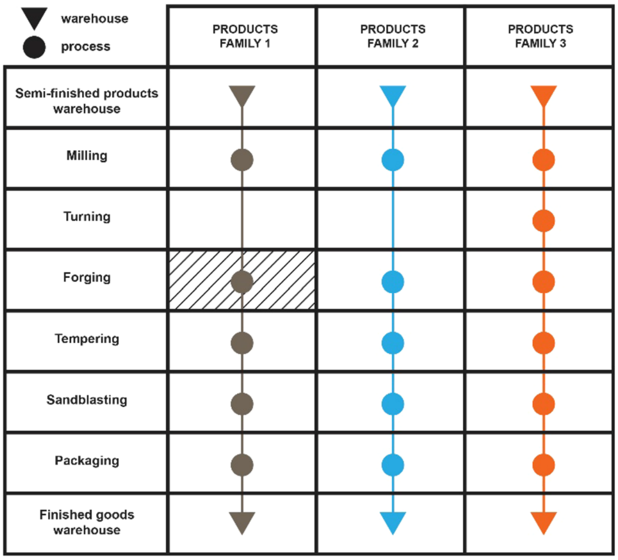

Fig. 6 The routing sheet corresponding to the three product families manufactured in the plant. Turning and milling are necessary stages for the creation of the standard metal shank. Forging is used to shape the plank, while the subsequent tempering and sandblasting phases produce the needed metallurgical features for the finished goods. Finally, the packaging is essential for shipping the products to the customers. Each stage might slightly differ from another dependently on the related product. The case study is focused on the forging activities of the first family of products (highlighted with the oblique lines pattern)

4.2 FRAM traditional steps

The first three steps (FRAM step 1, FRAM step 2, FRAM step 3) of the approach described in Sect. 3.3 are not the core focus of this research paper, since they are mainly based on a previous research work, conducted using multiple data collection techniques and data modeling. In particular, data collection was based on multiple types of sources (e.g., documental studies, focus groups, interviews) and constituted the starting point for the development of a Monte Carlo simulation framework, similar to the one depicted in Patriarca et al. (2017d), a, c. The framework relied on a three-dimensional phenotype association, i.e., timing, precision and ergonomics.

Following the data collection process, with the aim of representing real work activities inasmuch faithfully as possible, a FRAM (calculated) instantiation depicting Work-As-Done, accounted for 52 functions, among them 8 were background functions. Figure 7 sketches the model, as for a traditional FRAM representation. The latter does not offer a clear understanding of the system's properties, due to the overwhelming complexity generated by the number of functions and couplings. The interested reader will find an exhaustive description of the modeling efforts in Gattola et al. (2018).

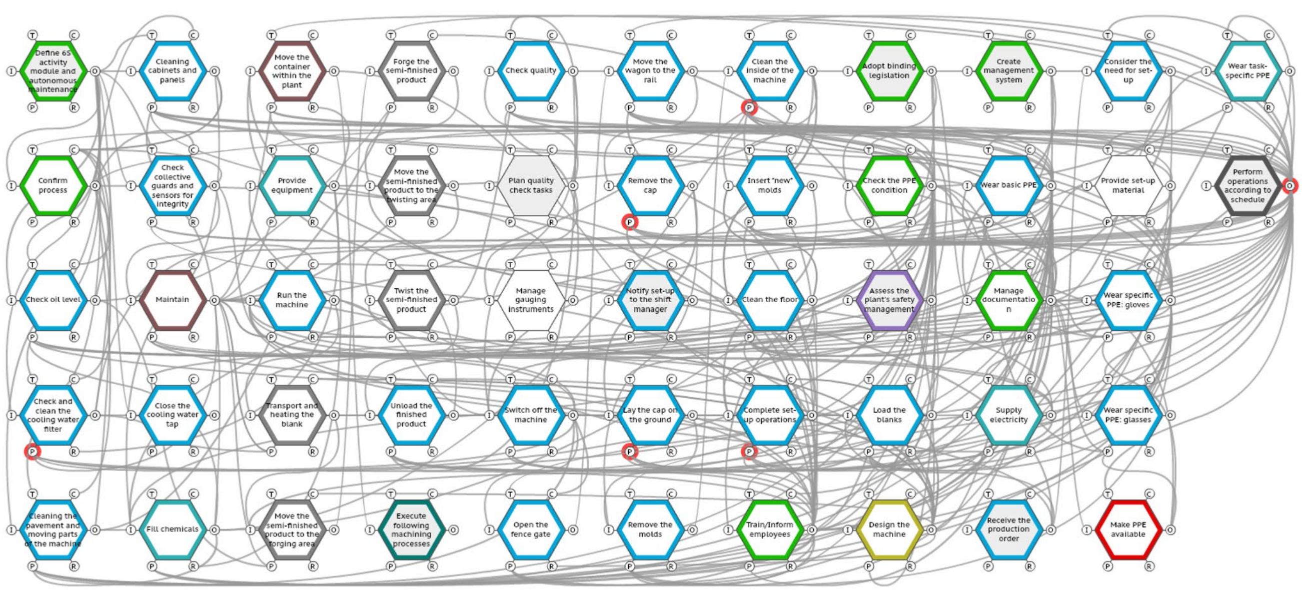

Fig. 7 The WAD calculated instantiation related to the forging operations. Different colors represent the nine agents involved in the process: a postworker (blue), a milk-runner (light-blue), a maintenance technician (brown), a safety manager (green), the personal-protective-equipment personnel (red), a machine designer (yellow), an auditor (purple), the personnel involved in auxiliary activities (white) and the forging machine (gray)

Figure 7 shows a moderately detailed instantiation, whose practical use of FRAM is hampered by its semantic richness. In text format, it becomes a long list of activities, exacerbated by many dependencies (e.g., coupling, aspects); in graphical terms, the hexagon-based representation is even more cluttered. In these cases, without relying on IT support, the usefulness of FRAM as a tool to manage organizational dissonance (Vanderhaegen and Carsten 2017) collapses: its informative power is limitedly helpful since it describes too many elements and respective relationships cannot be easily understood.

This concept remains valid in the context of resilience engineering. Resilience is indeed related to the ability of the system to adjust its behavior by dealing with disruptive events, dynamically, in a sort of "visual piloting" (Ruault et al. 2013). The system must self-guarantee a certain degree of situational awareness to achieve the desired performance.

Each individual operator continuously compensates for allowing the actual behavior of the system to be as close as possible to the desired one, sometimes deviating from their prescribed work activities. Over time, these deviating activities may become routine and no one is able to assess how system state is actually close to safety margins. Ruault et al. (2013) have called it a "visual pilot, but without visibility".

Even if an expert analyst identified the need for interventions, he/she would have difficulties in sharing them, through a traditional FRAM model. This latter does not provide enough conveyable evidence to lessen the cognitive dissonance of operators involved, both sharp-end and blunt-end ones. As for a feedback received during our analysis: "it is better to visual pilot without visibility on your own, than to rely on unintelligible instruments".

Table 1 Some descriptive data of the FRAM weighted multilayer network subdivided per layer

Layer	Number of nodes per layer	Number of edges per layer	Mean path length
Input	50	62	5.4
Precondition	44	146	1.6
Resource	8	7	1
Control	20	22	1.5
Time	46	53	1

As explained in Sect. 4.3, the multilayered network representation allows representing in a compact and conveyable way relevant information and, above all, it may represent a support tool for more deeply exploiting the semantic richness of FRAM.

4.3 Multilayered network representation

The network (direct) is formed by nodes (functions) distributed on five layers, each corresponding to a possible interaction type between the Output of a function and one of the

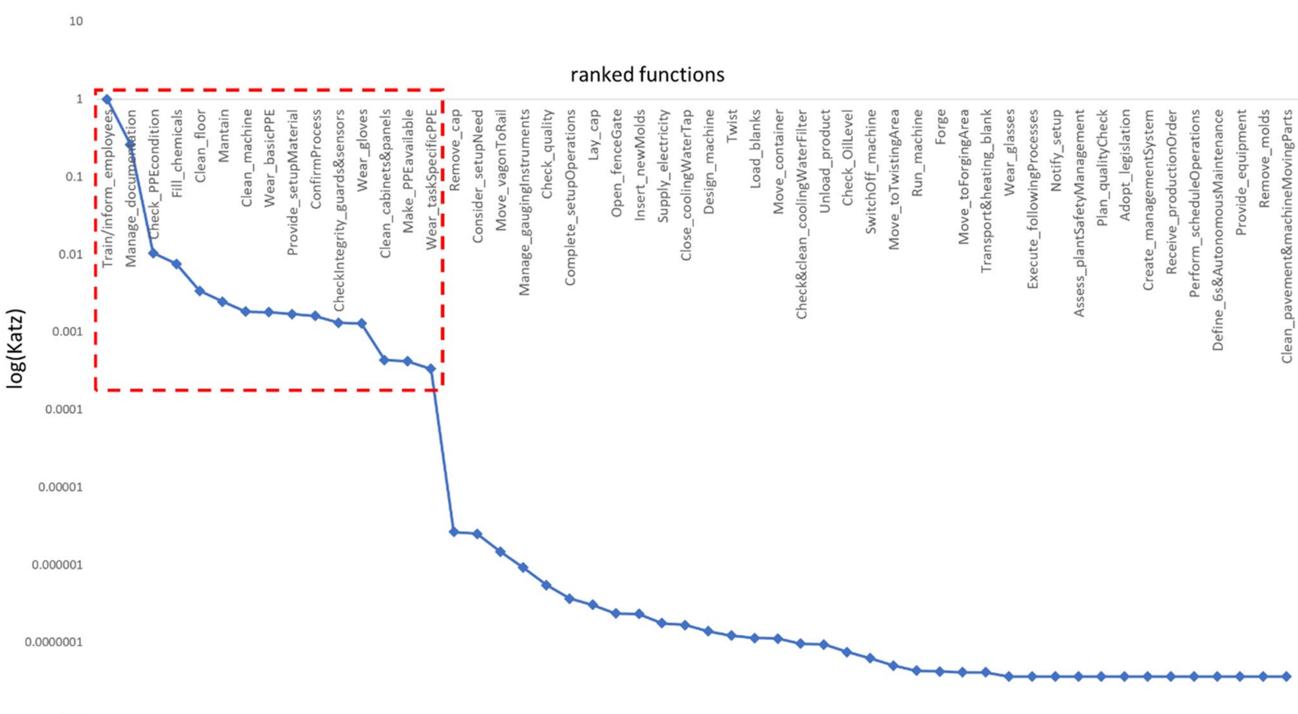

Fig. 8 Scree test using Katz. The first 15 functions are highlighted by a red dashed box

Table 2 Instantiation's functions ranked by Katz

Ranking	Katz
1	**Train/inform_employees**
2	**Manage_documentation**
3	**Check_PPEcondition**
4	**Fill_chemicals**
5	**Clean_floor**
6	**Mantain**
7	**Clean_machine**
8	**Wear_basicPPE**
9	**Provide_setupMaterial**
10	**Confirm_Process**
11	**Check_Integrity_guards&sensors**
12	**Wear_gloves**
13	**Clean_cabinets&panels**
14	**Make_PPEavailable**
15	**Wear_taskSpecificPPE**
16	Remove_cap
17	Consider_setup_Need
18	Move_vagonToRail
19	Manage_gaugingInstruments
20	Check_quality
21	Complete_setupOperations
22	Lay_cap
23	Open_fenceGate
24	Insert_newMolds
25	Supply_electricity
26	Close_coolingWaterTap
27	Design_machine
28	Twist
29	Load_blanks
30	Move_container
31	Check&clean_coolingWaterFilter
32	Unload_product
33	Check_OilLevel
34	SwitchOff_machine
35	Move_toTwistingArea
36	Run_machine
37	Forge
38	Move_toForgingArea
39	Transport&heating_blank
40	Wear_glasses
41	Execute_followingProcesses
42	Notify_setup
43	Assess_plantSafetyManagement
44	Plan_qualityCheck
45	Adopt_legislation
46	Create_managementSystem
47	Receive_productionOrder
48	Perform_scheduleOperations
49	Define_6 s&AutonomousMaintenance
50	Provide_equipment
51	Remove_molds
52	Clean_pavement&machineMovingParts

The first 15 bold functions constitute the foreground functions of the Base instantiation. The remaining 37 functions are sketched by only two background functions which are set to verify the closeness of the filtered system

five inputs (with minor "i") in downstream (Output–input coupling). A given function is not included in a certain layer, if for that function there is no downstream connection with the downstream aspect corresponding to that layer. The network has been built by assigning to the intralayer couplings of the same value obtained during the assessment stage. Remembering that weight 1 corresponds to a situation in which there is no particular variability or damping or amplification phenomena, this value has been used for all interlayer connections, as no further hypotheses are available. At this point, it should be remembered that the variability assessment process defines a semi-quantitative variable through an ordinal measure, which is not numerable (e.g., a value 48 is certainly more critical than value 2, but it does not imply that this latter has magnitude 24 times greater).

The FRAM instantiation depicted in Fig. 7 includes 52 functions (nodes) and 290 couplings (edges). These latter are representable through a multilayer network distributed over the five layers. The least populated layer of the network is the Resource layer, with only eight nodes involved in an Output–Resource relationship. The majority of the couplings are of the type Output–Precondition as highlighted by density (edge/node ratio) of the intralayer Precondition network (cf. Table 1).

The tensor representation has been developed through MuxViz routines. MuxViz is an open-source software specifically developed to analyze multilayer networks (De Domenico et al. 2015) relying on R programming environment.

4.4 Functional prioritization

In an extended FRAM model such as the walk-through application, there are many functions that have been defined to describe properly the processes involved. Many of those functions are usually added just for modeling purpose and are characterized by a low critical score. In a "simplexity" perspective (Colville et al. 2012), functions can be ranked according to their own Katz; model boundaries can be set by a threshold value used as a filter. The "scree test" is a dimensional reduction method of multivariate analysis that is well suited for choosing which values can be ignored (Raîche et al. 2013). Using Katz, the scree test can be represented graphically with a two-dimensional graph where the vertical axis is the Katz values (in logarithmic scale), and the horizontal axis represents the functions ranked accordingly to decreasing Katz (Fig. 8).

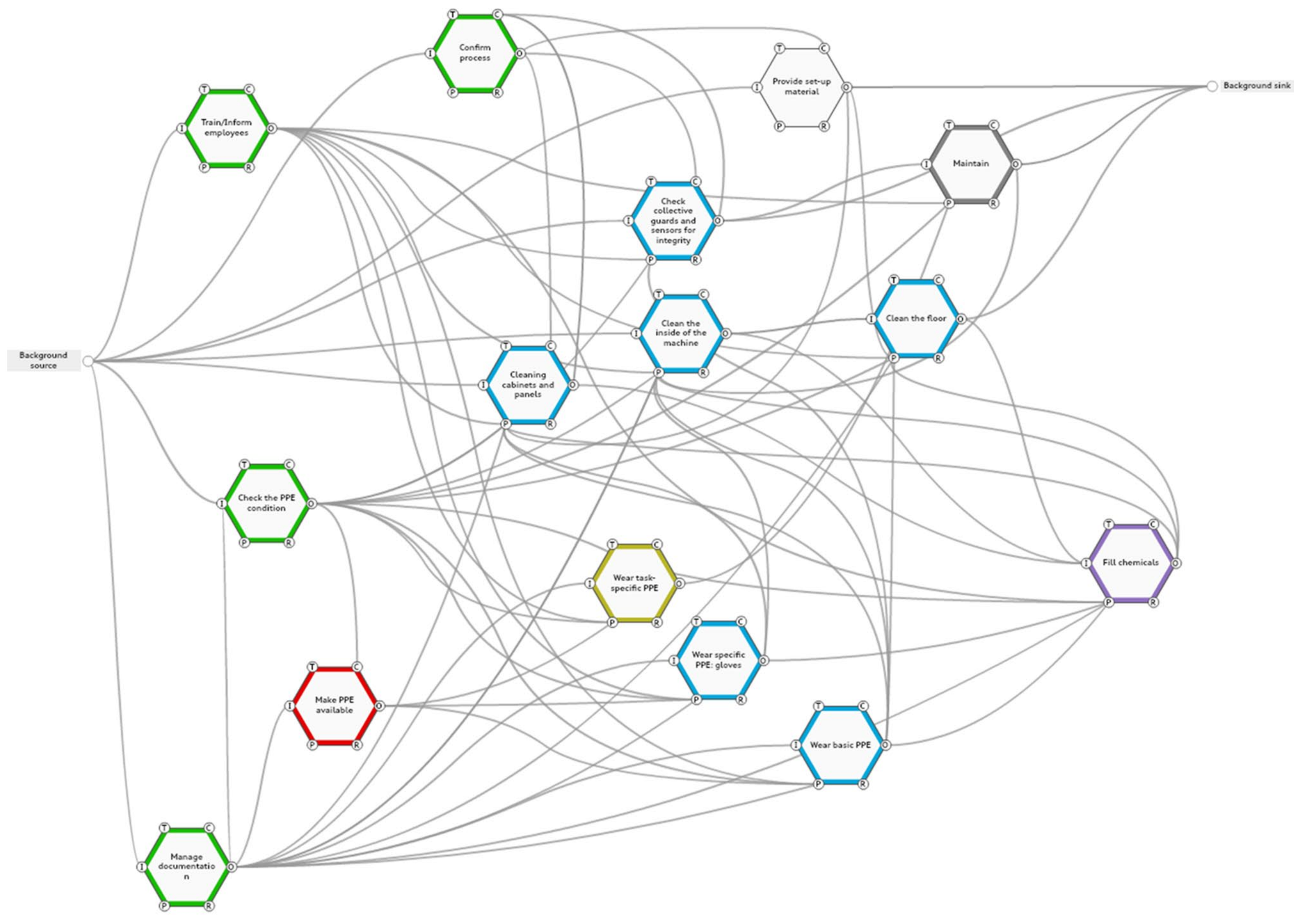

Fig. 9 Hexagon-based representation of FRAM Base instantiation

The scree test at this point prescribes identifying the values that refer to the curve's knees; usually the first knee is chosen (that in our case filters only 3 functions, which are actually largely more critical than the following ones). Since we are interested in focusing on a significant portion of the model, we prefer a larger amount of functions to be included, and thus we selected the third knee that allows us to consider the first 15 functions. Between the second and third knee, functions have more or less the same Katz, but beyond the third knee they acquire very lower values. Table 2 shows functions ranked by Katz, highlighting the filtered ones.

The results have been validated through a focus group with the experts involved in the model building, who confirmed the central roles of the 15 functions highlighted in Table 2.

4.5 Instantiation building

Starting from the filtered FRAM instantiation (hereinafter called Base instantiation), additional instantiations can be generated by suggesting variants that are likely to be viable. The alternative instantiations here proposed are some variants of the Base one, involving the functions <Train/inform_employees>, <Manage_documentation> and <Check_PPEcondition>. These latter are the first three functions in the scree test, identified by the first knee (Fig. 8).

4.5.1 Base instantiation

The Base instantiation has the 15 prioritized functions plus two background functions used to close the model (see Fig. 9).

4.5.2 Alternative instantiation #1: "Foot"

Generally, it is very difficult to intervene on a single activity of a socio-technical system without altering it in some way, at least in part. From a conceptual point of view, this concept implies generating at least one other function. Sometimes, such additional function may be outside the scope of the model. This is exactly what happens in

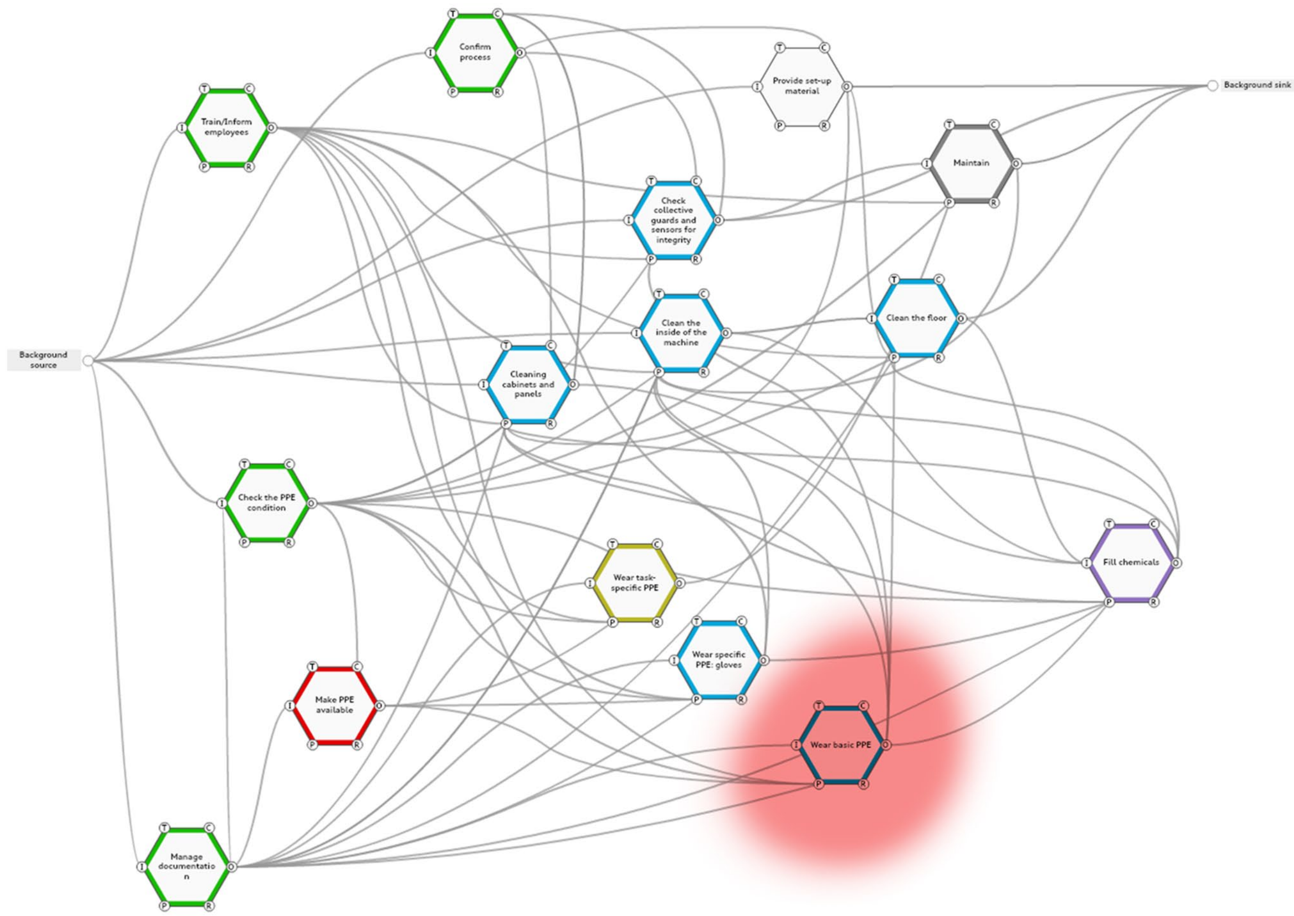

Fig. 10 Hexagon-based representation of FRAM instantiation "Foot". Red area refers to the function being suppressed in this instantiation

the first proposed alternative instantiation (called "Foot", since it refers to footwear).

The <Wear_basicPPE> function corresponds to wearing protective shoes as a Precondition for the cleaning activities of the starting model made up of 52 functions. This action constitutes a system inefficiency that can be eliminated by using shoes resistant to aggressive chemicals regardless of the activity carried out directly in the locker room. In this way, the activity of wearing basic personal safety devices is eliminated, i.e., the corresponding function is not present in this alternative instantiation. Nevertheless, the substituted activity of wearing chemical-resistant footwear simply ends up outside the bounds of this model. As shown in Fig. 10, the function disappears, and the connections involved are also lost.

4.5.3 Alternative instantiation #2: "Gam"

The highest Katz value is associated with the <Train/inform_employees> function. Currently it is carried out in the traditional way: some sporadic training activity is provided but, as confirmed in the validation with experts, are not very effective. One issue is that the evaluation of the effectiveness level of training/information activity is a long and expensive process and, consequently, rarely implemented.

This alternative instantiation proposes the adoption of an integrated gamified training/information/evaluation system, given the encouraging results obtained from training paradigms adopted in similar contexts (Bellamy et al. 2018; Patriarca et al. 2019). Improved staff engagement reduces the downstream variability of <Train/inform_employees>. However, as mentioned above, this solution requires the inclusion of an additional function <Provide Gamified Training/Information> that controls <Train/inform_employees>. <Gamified Training/Information> requires specific knowledge and cannot be ensured by the safety manager (green agent), but must be implemented by staff specialized in serious games and gamification (an additional black agent) as shown in Fig. 11.

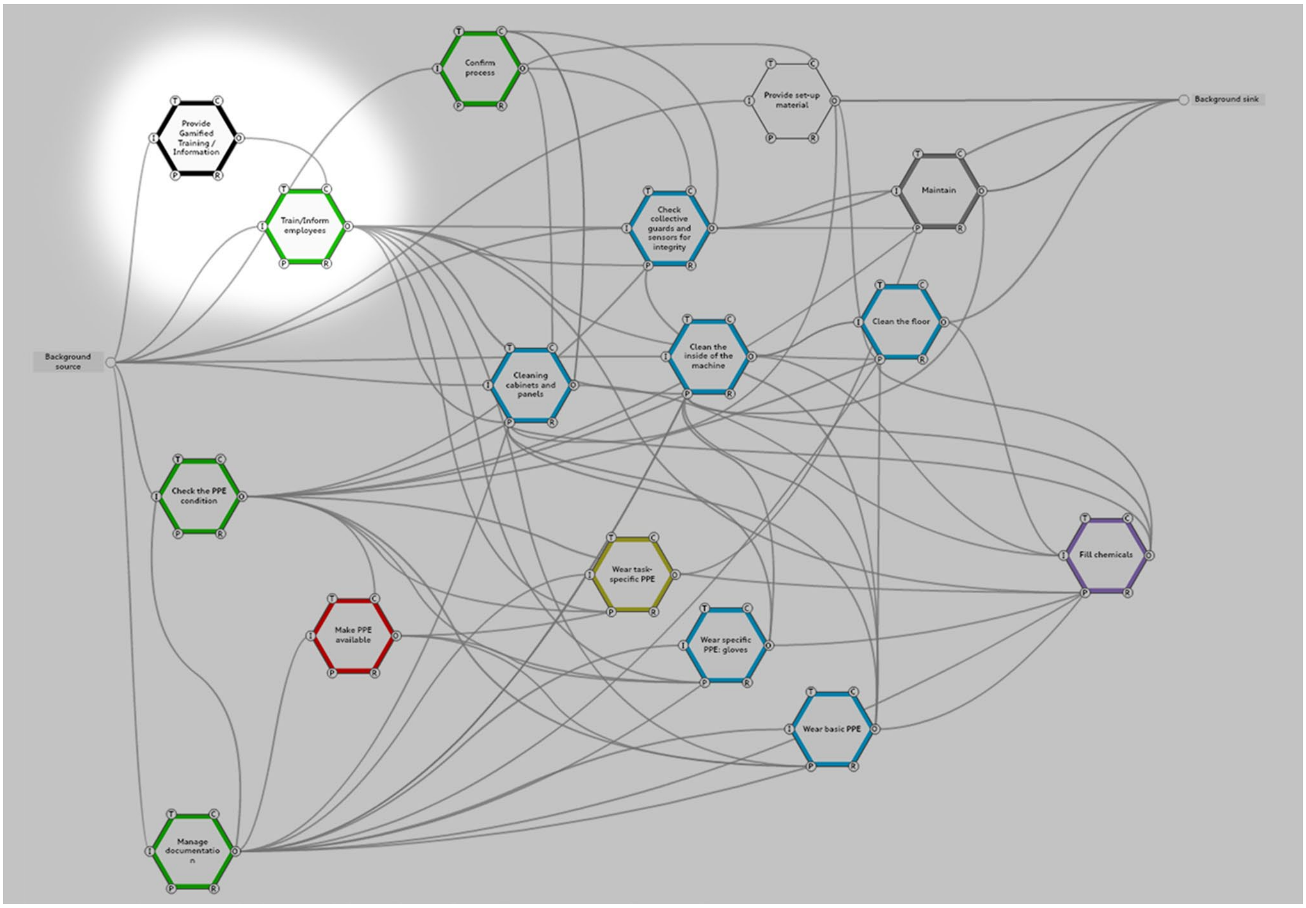

Fig. 11 Hexagon-based representation of FRAM instantiation "Gam". White area highlights the additional function, and its main dependencies

4.5.4 Alternative instantiation #3: "PPE"

<Check_PPEcondition> is a function that provides in Output the state of the PPE. Regulations prescribe that the organization must monitor the conditions of all PPEs. In the Base instantiation, <Manage_documentation> is the function that provides list check of PPEs, on a weekly basis, regardless of the specific PPE. In this alternative instantiation, this check is carried out on a specific time interval for each type of PPE. For this instantiation to take place, the safety manager must perform a new task <Task_specific_PPE_list_check> that modulates the activity <Check_PPEcondition> entering into the Time aspect (see Fig. 12). Such activity is envisioned to be carried out in a testing period of about 8 weeks to properly set the specific timeframes.

4.6 Tensorial representation of instantiations

The single calculated instantiation (i.e., the set of values of the active coupling in the considered state of the system under examination) defines an algebraic structure (the shell of the corresponding tensor) that can be, in principle, occupied by other instantiations.

These latter are made from this support by simply turning on or off the corresponding coupling (i.e., occupying the shell with other values). In the Base instantiation, the corresponding shell allows representing 17 functions (the 15 foreground plus the 2 background to the boundaries) on three layers (since neither the Resource layer nor the Time layer are needed, i.e., none of the functions is defined through them. Strictly speaking, you could leave the Resource and Time layers present, but for illustrative purposes we prefer to show the shell strictly necessary to represent the instantiation under examination) as in Fig. 13.

When considering alternative instantiations, the associated tensors are built by modifying the Base tensor. The necessary shell for Foot instantiation can be obtained starting from the Base instantiation by deleting from each layer, the row and column corresponding to the function deleted (see Fig. 14).

At this point we want to draw the reader's attention to the evident substantial difference between instantiations

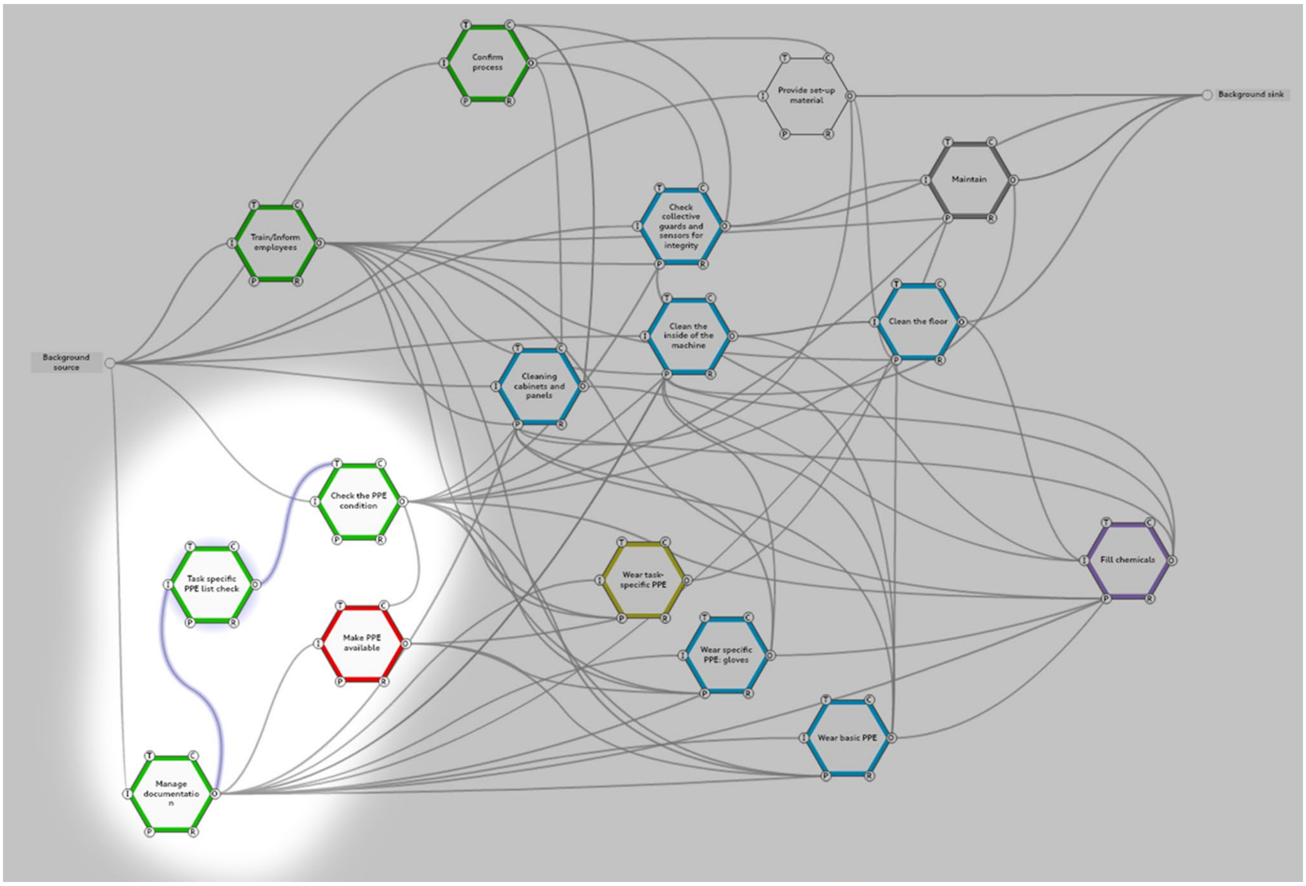

Fig. 12 Hexagon-based representation of FRAM instantiation "PPE". White area highlights the additional function, and its main dependencies

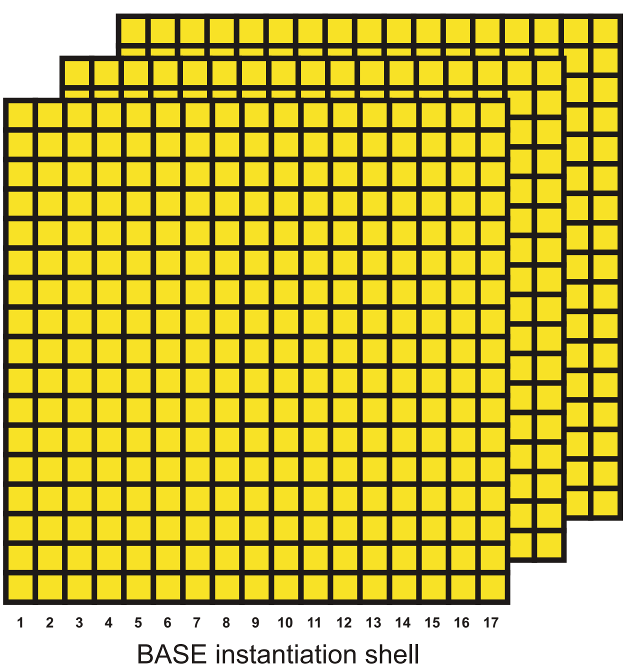

Fig. 13 Shell corresponding to tensorial representation of FRAM Base instantiation

and model. For example, when comparing Base and Foot instantiations, their strictly necessary shells are different. However, the corresponding model must be defined by a unique shell, which in this case is the Base shell, since it is possible to obtain both Base and Foot instantiations by turning on the corresponding values of couplings between associated functions.

The tensorial representation of Gam instantiation is obtained by adding a function to Base instantiation, similarly to PPE instantiation. The difference is that in case of Gam, the shell size is $18 \times 18 \times 3$ (Fig. 15), while in PPE, another layer (Time) is involved, therefore the shell strictly necessary has a size of $18 \times 18 \times 4$ (Fig. 16).

4.7 Tensorial representation of FRAM model

Starting from the results obtained in Sects. 4.5 and 4.6, the size of the shell strictly necessary to represent the FRAM model is $19 \times 19 \times 4$, as depicted in Fig. 17, whose colors reflect functions involved in all the alternative instantiations.

This structure will allow the algebraic comparison between the instantiations.

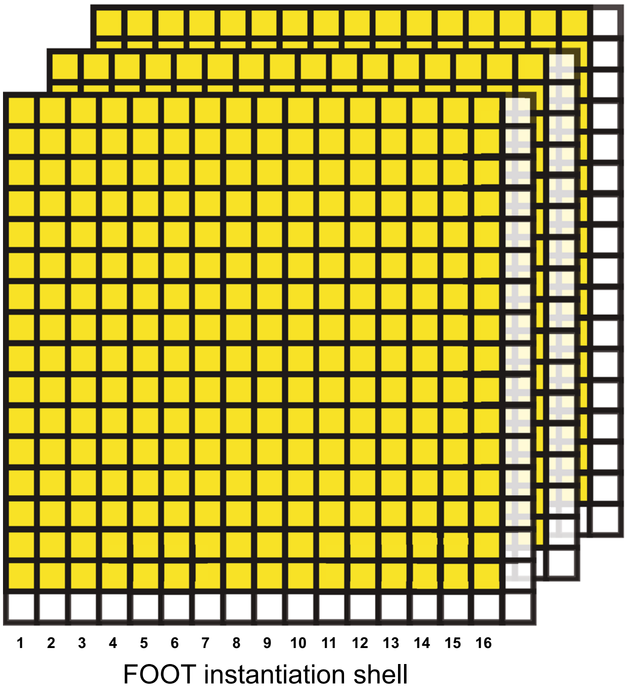

Fig. 14 Shell corresponding to tensorial representation of FRAM Foot instantiation

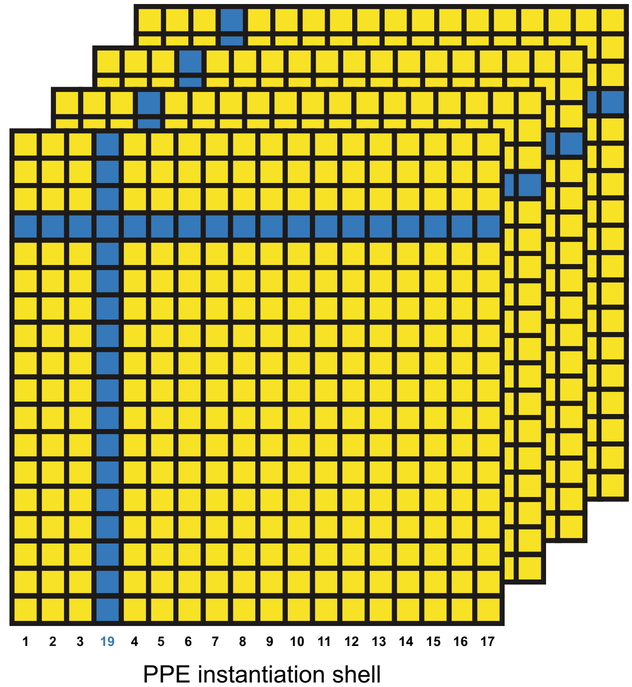

Fig. 16 Shell corresponding to tensorial representation of FRAM PPE instantiation

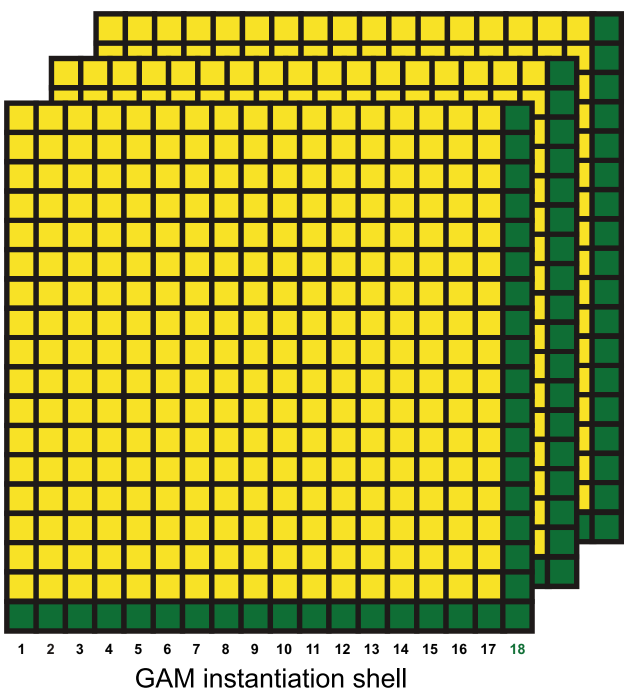

Fig. 15 Shell corresponding to tensorial representation of FRAM Gam instantiation

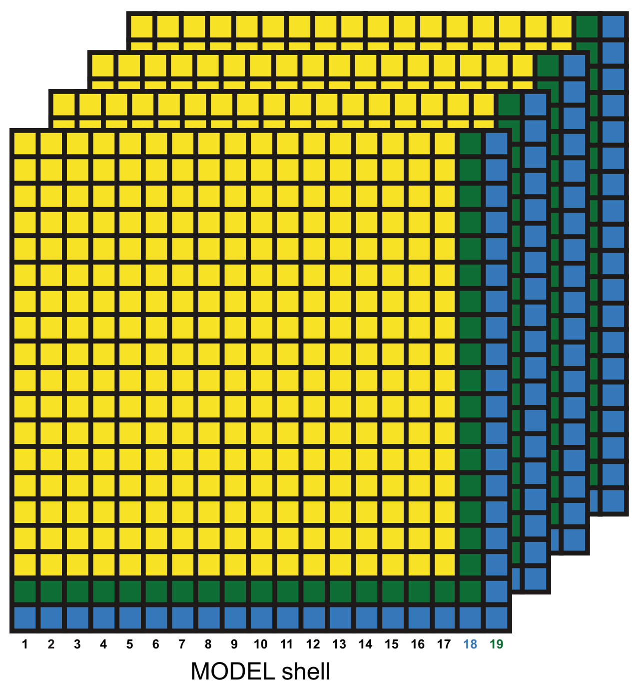

Fig. 17 Shell corresponding to tensorial representation of FRAM model (Template for tensors comparison and benchmarking)

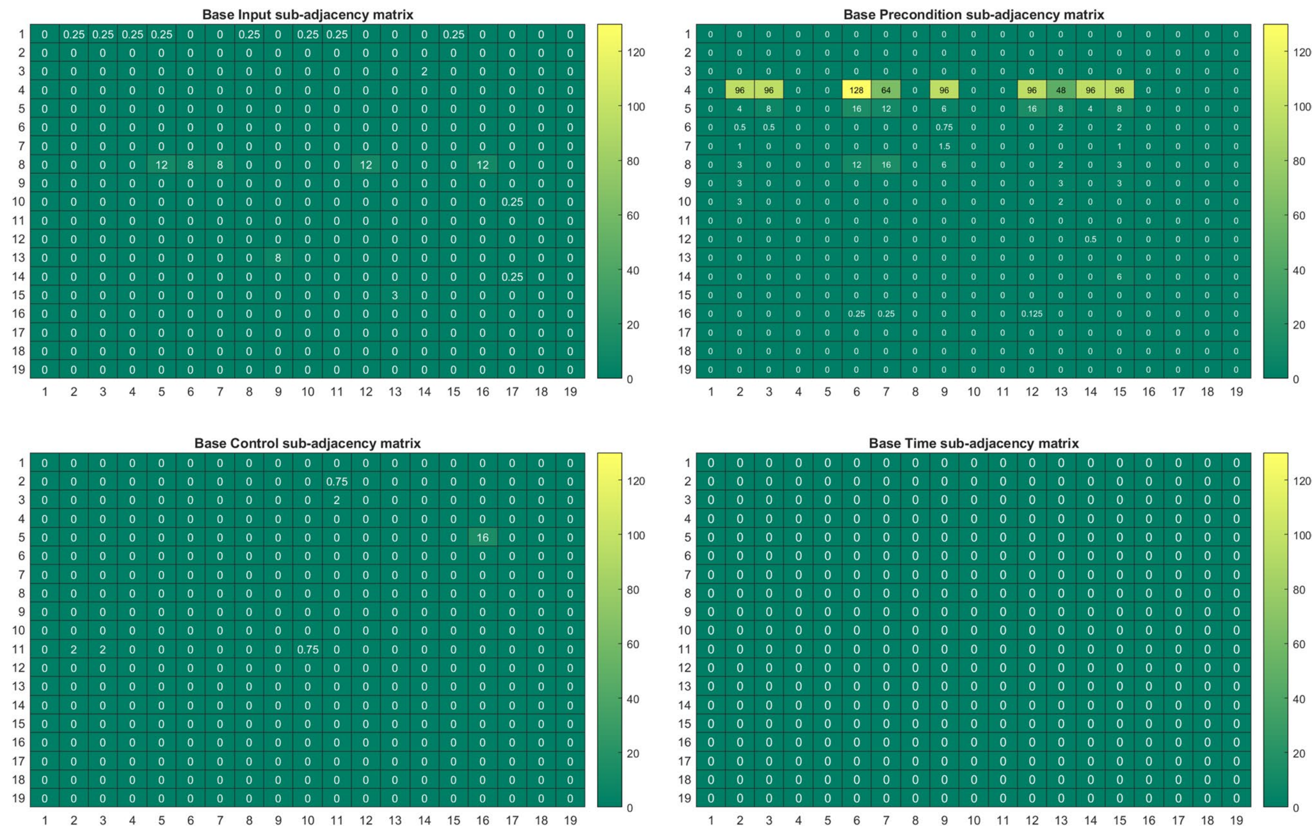

Fig. 18 Heatmap representation of tensor for Base instantiation

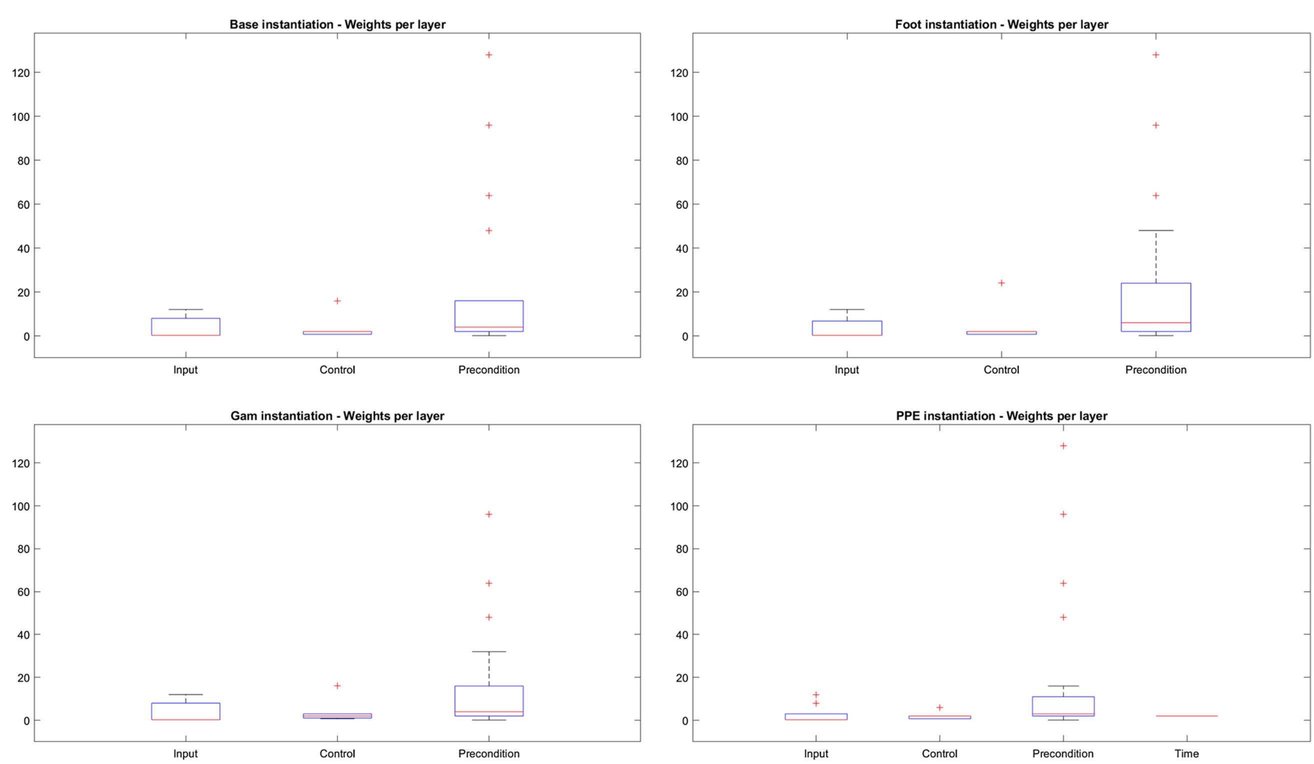

Fig. 19 Box-plot of couplings' weight values

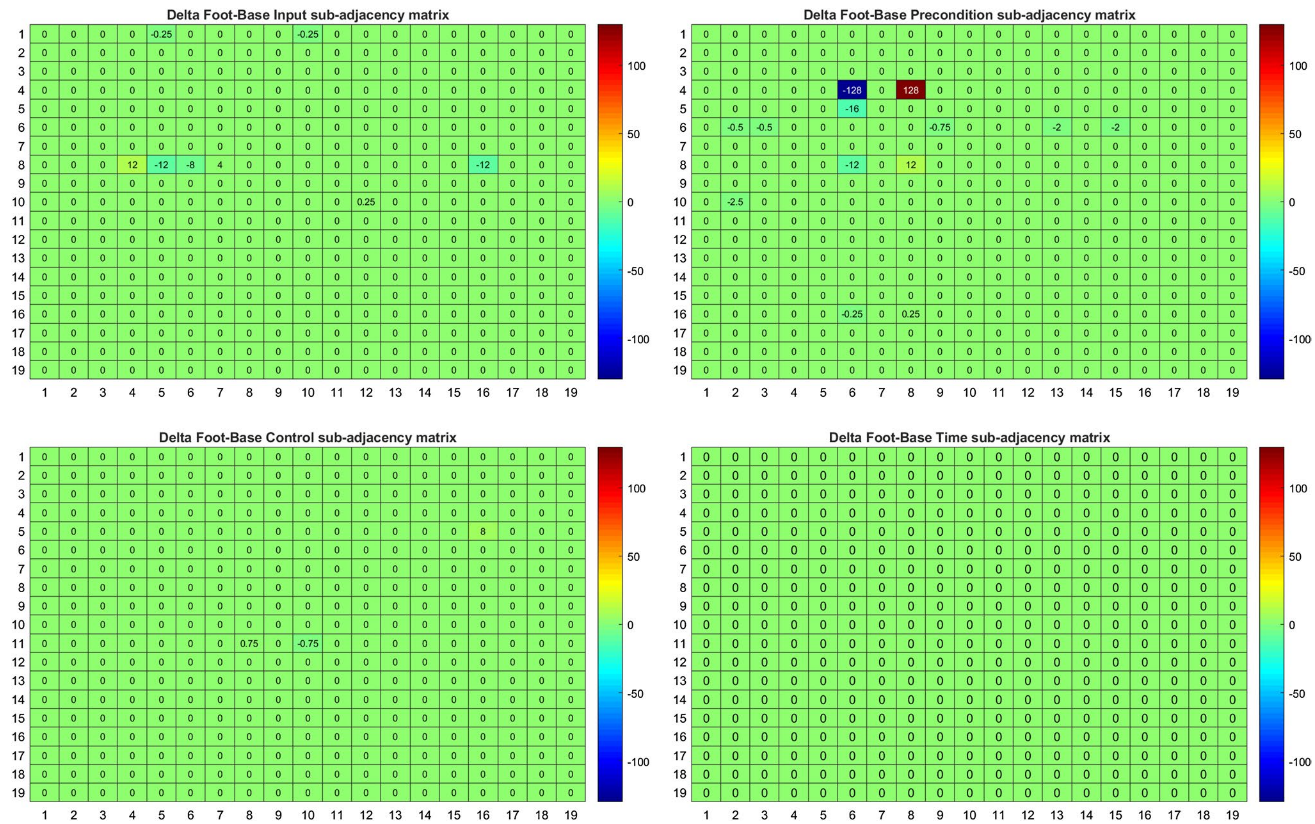

Fig. 20 Heatmap representation of performance benchmarking between Foot and Base instantiation

4.8 Benchmarking and experts validation

Once the model shell is developed, it is sufficient to populate it with the values corresponding to each instantiation. The information contained in the corresponding tensor can be communicated easily and significantly, for example with heatmaps in false colors mapped on the value (i.e., the weight) of the corresponding coupling. For example, Fig. 18 depicts the heatmap associated with the tensorial representation of Base instantiation: most critical situations occur on the Precondition layer, generally low values are shown on Control and Input layers, while on Time layer there is no link (i.e., all values are null). Similar figures can be obtained for the other three instantiations. For example, the coupling from Function 4 directed to Function 6 is the most critical (score 128, yellow cell) on Precondition layer, and on the whole multilayer network.

In this case, the representation limits the impact of dissonance caused by the new information, especially if compared to hexagon-based representations as the one in Fig. 7. The impact of dissonance can be integrated into the knowledge by the new knowledge acquired (Vanderhaegen and Carsten 2017).

At this point, it is relatively immediate to obtain statistical information on the distribution of variability scores in the different solutions, which can be helpful to represent synthetically the alternatives. Figure 19 depicts the couplings' weights through box plot diagrams for each layer.

Furthermore, at this point, it is possible to start a benchmarking process and present the results through additional heatmaps. These latter are obtained considering the difference between one alternative instantiation and the Base instantiation, and depict positive (i.e., worsening scenario) or negative values (i.e., improvements). Figures 20, 21, and 22, respectively, present the differences between Foot, Gam, PPE instantiations when compared to Base instantiation.

The alternative instantiations can be ordered following such differences. In a decreasing order: Gam, PPE, Foot, Base. Furthermore, instantiations can be ordered in terms of feasibility. Feasibility is used here as a generic notion that subsumes the concepts of implementation (mainly cost, but also implementation difficulties due for example to cultural resistance, etc.). For the purpose of this research paper, a qualitative estimation is suggested, which implies the following order: Base, Foot, PPE, Gam.

As a conceptual summary of the benchmarking process, presents a two-dimensional plot (feasibility vs performance) which is aimed at supporting the decision-maker in the identification of the most suitable solutions for the system at hand, due to the Resources' constraints

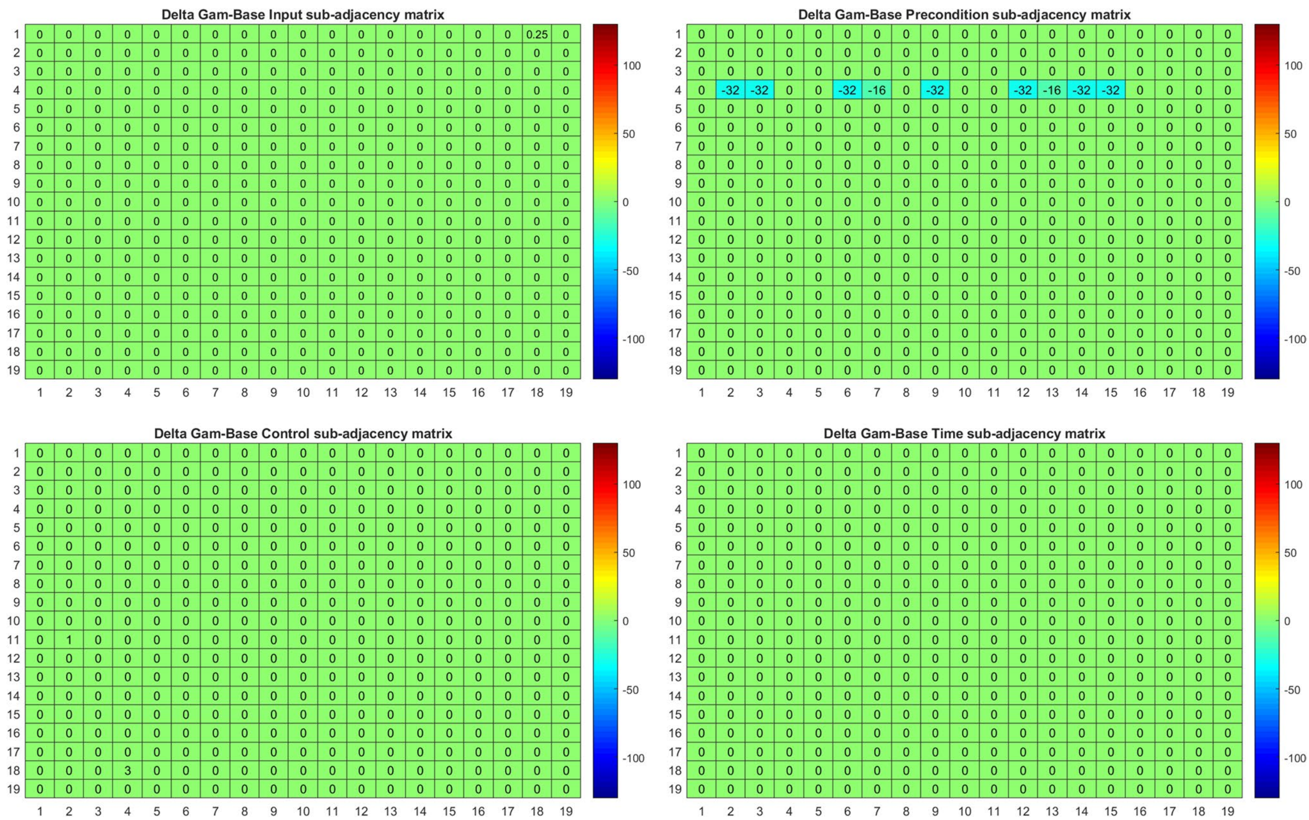

Fig. 21 Heatmap representation of performance benchmarking between Game and Base instantiation

and the desirable performance targets. The assessment should be systemic to encompass both the role of technology, people (at a cognitive and physical level), and procedures in the work domain (Fig. 23).

Once selected the alternative solution(s) to be implemented, the model should be revised to take into account the work domain revision. Note that in this phase, it is worthy to iterate the proposed methodological approach, in a continuous improving process. The model should be also based on different data collections, to make sure that the developed model is actually corresponding to the envisioned reality.

5 Conclusion

The FRAM has been widely recognized as a method to model complex socio-technical systems minimizing both post hoc bias and confirmation bias. Starting from the analysis of normal circumstances, the FRAM can be used for prioritizing mitigation actions after the identification of those system's functions having the potential for resonating. Nevertheless, especially vast models suffer for the identification process, also due to the overwhelming complexity of the representation itself.

This work shows that any FRAM instantiation might be interpreted as a multilayer network, allowing to bridge the gap between network analysis and FRAM-based analysis of complex systems. This approach, managing systematically couplings and variability information, lessens the effort needed for identifying relevant functions by means of out-of-the-box network centrality indexes (in particular, Katz is shown as a significant metric). The concept of function relevance for a socio-technical system can be broadened by adopting different criteria of analysis or prioritization, not limited to the functions' variability but to their "network" role as well. Moreover, since an instantiation is a digraph, the same network approach allows the building of key performance indices or leading indicators, based on the concept of Authority or Hub measures, respectively, (e.g., making more actionable steps 4 and 5 of the leading indicators identification method (Raben et al. 2017)).

The walk-through application confirms the isomorphism between a FRAM instantiation and a five-layer multilayer network. We want to stress the concept that the former is only the simplest—yet semantically rich—among the possible tensorial representations of a FRAM instantiation. The usage of higher ranks adjacency tensors

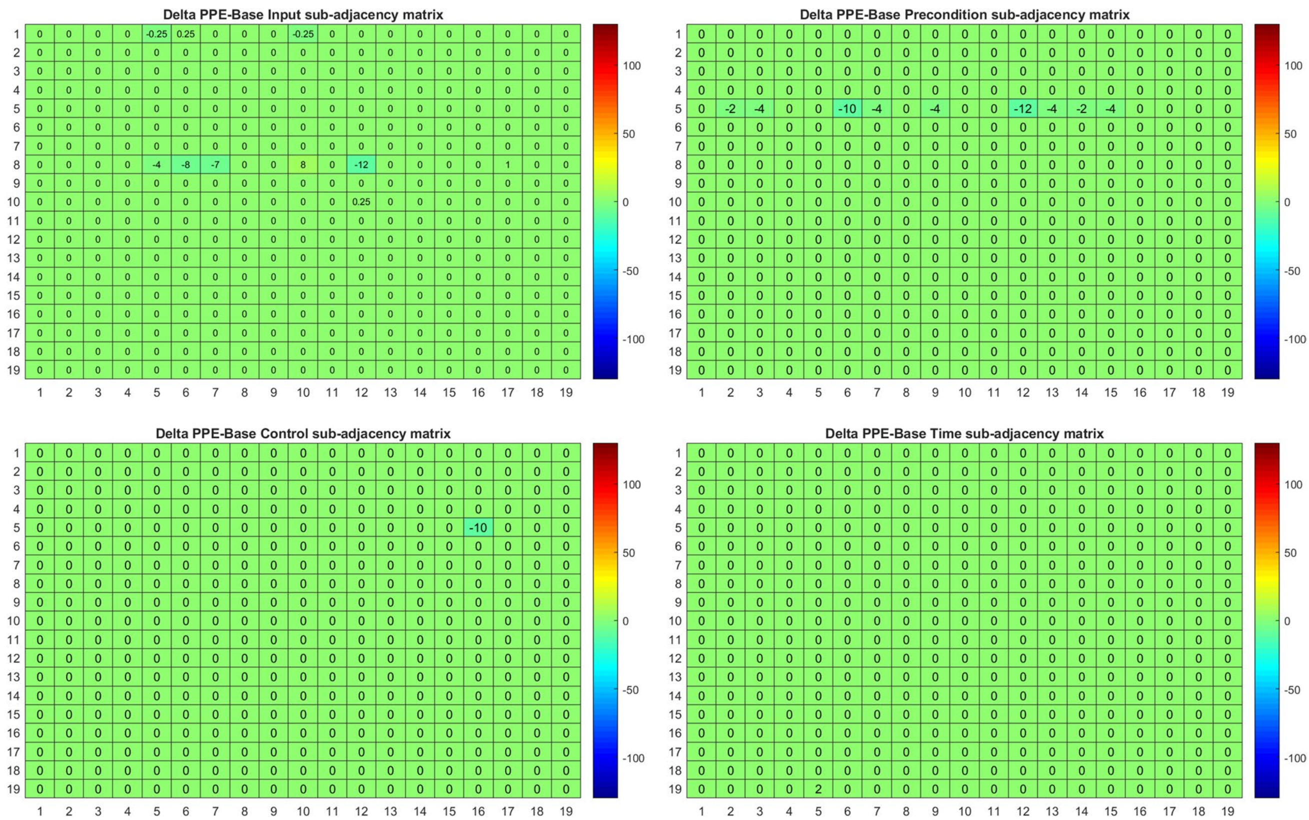

Fig. 22 Heatmap representation of performance benchmarking between PPE and Base instantiation

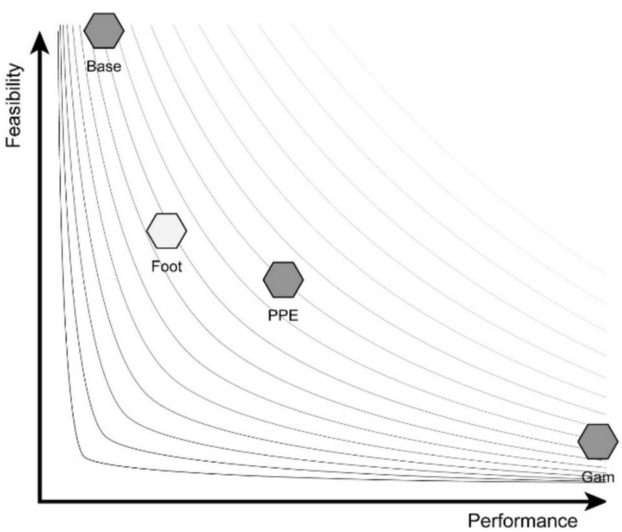

Fig. 23 Feasibility vs Performance analysis of instantiations

allows compact and powerful representations, including temporal relationships (i.e., ordinal interlayers edges), specific functional agency information and abstraction hierarchies (e.g., interconnected networks of networks). Although beyond the scope of this work, at this point it is worth taking up Hofstadter's quotation initially mentioned in Sect. 3.2 to further delineate the conceptual root of isomorphism (Hofstadter 1999). Strictly speaking, both the multilayer digraph and the instantiation are isomorphic to the algebraic structure that encodes them as well: the tensor shell. It is the tensor as an abstract algebraic entity that persists in temporal evolution, not the single instantiation, nor the specific digraph, both corresponding to that particular tensorial shell populated by values corresponding to a single temporal frame. We believe that such tensorial representation can be a viable support also to represent somehow the so-called emergent instantiations.

To date, the main flaw of the present attempt resides in the way weights are obtained. The SMEs assessment procedure provides measures having only ordinality for which linear combination is not valid (Patriarca et al. 2017d). Although network analysis is often applied in contexts where the measures suffer from the same deficiencies (e.g., Likert scale of social interaction), and for which some metrics are still available and meaningful, this limit does not allow us to fully exploit the power of network analytics. As such, it would be particularly helpful to envisage an operational weighting schema of FRAM couplings that contemplates an algebra of variability, paving the way to a potentially complete and quantifiable framework for FRAM models. In principle, if couplings' weights were normalized, the adjacent tensor could be traced back to a transition tensor, and the system interpreted in terms of a Markov chain, thus in turn authorizing interpretation of emergent instantiations as stationary distributions.

Finally, as the functions (nodes) that constitute the model are given, and inherently the corresponding adjacency tensor' shell, hence, it is in principle possible to span over any desired instantiation simply by operating on the tensor's elements. In practice, this activity consists of turning on/off sets of couplings corresponding to the instantiation at hand, which becomes a central step in every potential FRAM scenario-based analysis (Wachs et al. 2019). Finally, starting from an instantiation, it would be possible to beget other instantiations, eventually bridging the actual gap between calculated and emergent instantiations, and possibly extend the same reasoning to entire FRAM models.

In summary, the multilayer network representation of FRAM offers a number of advantages. Firstly, network analysis methods and tools are consistently made available; among these, centrality indices stand out as immediate ready-to-use tools for redefining the boundaries of the system under consideration. Secondly, it provides a support (i.e., the tensorial shell) for the activity of re-designing the investigated processes and the consequent benchmarking, enabling the simulation of envisioned scenarios. Thirdly, it support more objective and easily conveyable comparisons (e.g., WAD vs WAI, time-dependent instantiation comparisons). Slices of the tensor (i.e., individual layers) can be used to effectively communicate the instantiation's criticality status, layer by layer. The designer can thus propose alternatives that can be immediately inspected by the decision-maker (e.g., the blunt-end operator). Overall, these advantages have the potential for reducing organizational dissonance.

Acknowledgments The authors of this paper developed an IT solution based on VBA (Patriarca et al. 2018a) to perform the calculation over the FRAM instantiation and utilized the muxViz tool to measure multilayer centrality indexes (De Domenico et al. 2015).

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