FRAM TO ASSESS PERFORMANCE VARIABILITY IN EVERYDAY WORK: FUNCTIONAL RESONANCE IN THE RAILWAY DOMAIN

Patriarca R., Di Gravio G., Costantino F., Tronci M.
Department of Mechanical and Aerospace Engineering,
Sapienza University of Rome
Via Eudossiana 18 - 00184, Rome (Italy)
corresponding author: riccardo.patriarca@uniroma1.it

Abstract

This paper shows the possibility of enhancing the traditional FRAM structure by a semi-quantitative framework in order to increase FRAM's applicability for the analysis of complex systems. This innovative framework consists of defining numeric scores for variability, quantifying in a particular scenario the effects of interactions among functions. Rather than static and deterministic values, it assigns probability distribution functions to the scores, combining them by the aid of Monte Carlo simulation. The distributions, based on Subject Matter Experts' judgments and historic data, if available, allow obtaining an estimation of performance variability and its subsequent functional resonant effects. This semi-quantitative framework allows isolating the critical functions and the critical links among functions, considering non-linear and transient interdependencies. This paper explores the possibility of combining the Monte Carlo framework with an Abstraction/Agency framework recently introduced in literature, in order to make more evident and readable the model itself, maintaining a systemic functional perspective. Once addressed the criticalities and related them to different abstraction levels, it would be possible to plan for mitigating actions. The illustrative case study takes advantage of SMEs and several accident reports in the railway domain to illustrate the application of the proposed semi-quantitative multi-layer framework.

1 INTRODUCTION

In terms of risk and safety management, an interest in human factors became increasingly relevant late in 1980s, to cope with "new" types of accidents, such as the one at Three Mile Island (Hollnagel, Leonhardt, Licu, & Shorrock, 2013). A cause-effect perspective guided the development of methods and model, generally focused at identifying the best fixing strategy for those components most subject to a failure. Following the disasters of Challenger and Chernobyl, both in 1986, it appeared necessary to extend a risk and safety analysis taking into account organizational factors (Vaughan, 1996), (e.g.) adopting the well-established Probability Risk Assessment (PRA) (Stamatelatos, 2002).

In the last two decades, the acknowledgment of systems' complexity started acquiring interest in safety and risk analysis, being concerned with complex system failures and underlying socio-technical factors. Socio-technical systems imply both dual focus and joint optimization of two inter-related sub-systems: the social and the technical system (Pasmore, Francis, & Haldeman, 1982). Technological artefacts interact with individuals, groups, procedures, and even the whole organization, affecting everyday and long-term activities. Those non-negligible tight interactions imply the need of integrating the analysis of different tasks and processes, acknowledging - rather than simply reducing - their complexity and non-linearity. As a consequence, the "reductive tendency" of designers of complex socio-technical systems should be avoided, making room for a complexity management perspective (Pavard & Dugdale, 2006). On this path, this paper adopts the Functional Resonance Analysis Method (FRAM) to analyse a process in the railway domain, extending the traditional FRAM by a semi-quantitative and multi-layer framework.

2 AN INNOVATIVE COMBINED APPROACH FOR FRAM

FRAM aims at defining complex systems analyzing their functional aspects rather than their physical structure. It allows showing actual interactions, in terms of how a system actually performs in everyday work, adapting their functioning to deal with the variability of current operating conditions.

2.1. The Traditional FRAM

FRAM relies on four principles: equivalence of failures and successes, approximate adjustments, emergence, and functional resonance. The traditional building process of a FRAM model consists of four steps, i.e. identification and description of system's functions, identification of performance variability, aggregation of variability, management of variability. The proposed framework does not affect FRAM principles, but modifies its building steps, as detailed in §2.2 and §2.3. In the proposed framework, the basic element of a FRAM model, i.e. a function described according to six aspects (Input, Output, Precondition, Resource, Control and Time), remains the core of the analysis. For a complete and detailed description of FRAM principles and building steps, refer to Hollnagel's handbook on FRAM (Hollnagel, 2012).

2.2. A Multi-Layer Framework for FRAM

The idea of a multi-layer FRAM arises from the consciousness that in a complex system, a single representation does not allow describing and coping with different scenarios, each one characterized by different requisites. As argued by Rasmussen in 1970, it is beneficial to explore a complex work domain by his two-dimensional representation: the abstraction/decomposition framework. The decomposition (on x-axis) represents the physical aggregation levels of the system (from whole system to smallest components). The abstraction (y-axis) represents the degree to which the physical implementation of functions is maintained in the representation (Rasmussen, 1985). A representation in these two dimensions allowed describing and transferring the analysis of the work domain to different resolution levels.

On this path, a recently introduced framework in the field of risk and safety management is adopted: the Abstraction/Agency framework, combined with FRAM (Patriarca, Bergström, & Di Gravio, 2017). Even if its abstraction dimension follows the traditional Rasmussen definition, the agency dimension (x-axis) aims at exploring different abstraction levels following the perspective of different system's agents. The number of abstraction levels as well as the number of agents are not absolute, depending on the purpose of the analysis, and on the characteristics of the system itself. Once defined the agents to consider for the purpose of the analysis, the framework aims at managing the complexity of the resolution, allowing limited analyses only to significant abstraction levels. Furthermore, it allows filtering the functions (i.e. the hexagons) of a FRAM model, generating multiple representations of the same model at different abstraction levels, and/or for different agents. The framework helps giving sense to the spatial representation of the system, allowing a standard representation to increase the comprehensibility of the model. It is interesting to observe how this multi-abstraction level does not compromise the *method-sine-model* assumption of FRAM. It rather suggests a complexity management perspective, maintaining the scale invariance of FRAM, yet argued by Hollnagel himself (Hollnagel, 2012). Figure 1 sketches a theoretical Abstraction/Agency framework, representing the same generic FRAM function (function k-th) performed by a generic agent (agent g-th). Note that the n_g number of abstraction levels can be different for each agent, depending on the purpose of the analysis.

In a methodological perspective, for using the Abstraction/Agency framework, it is necessary to intervene in the first building step "identification and description of system's functions". Once the analyst has defined the functions at the n_g-th abstraction level following the traditional approach, he has to ascribe them to the g-th agent who actually performs it, who can be an individual, a group of them, an artefact, etc. Then, for each function at the n_g-th abstraction level, the analyst has to assign name and descriptions of the $(n_g - 1)$ functions at the upper abstraction levels, defining the respective function names. Note that those functions at the remaining $(n_g - 1)$ abstraction levels will be inherently defined in terms of the six aspects by a functional envelope of the functions at the n_g-th abstraction level. This approach is in line with the purpose of the Abstraction/Agency framework, which does not aim at developing different models of the same work domain (adding more hypothesis on its functioning), but creating different resolutions of the same work domain at different abstraction levels.

2.3. A Semi-Quantitative Framework for FRAM

Research on FRAM recently shows an increasing interest in variability and uncertainty modelling, combining the traditional method with other relevant approaches. For example, showing the benefits of checking paths of variability by the aid of the model checker SPIN (even if limited to simple systems) (Yang, Tian, & Zhao, 2017); using the Analytic Hierarchy Process (AHP) to increase objective assessment of functions' variability (Rosa, Haddad, & de Carvalho, 2015). Furthermore, Monte Carlo simulation has been used to explore variability, showing the benefits of its application in combination with FRAM in the air traffic management system (Patriarca, Di Gravio, & Costantino, 2017), and process plant (Patriarca, Di Gravio, Costantino, & Tronci, 2017). In a methodological perspective, Monte Carlo simulation affects the building steps "identification of performance variability" and "aggregation of variability", with inherent consequences even in "management of variability".

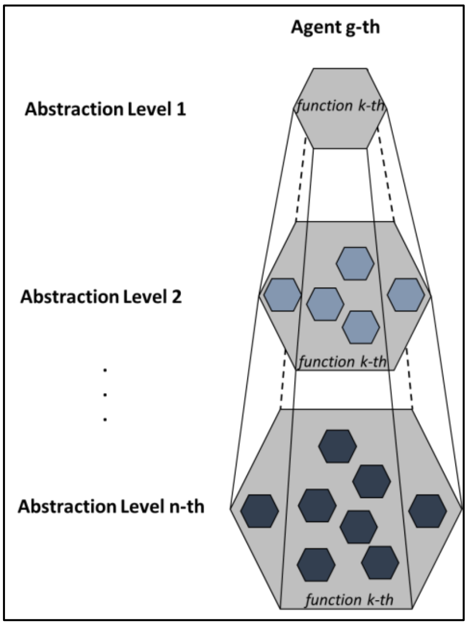

Figure 1. *Theoretical representation of the Abstraction/Agency framework. The hypotheses of fractality and scale invariance allows a multi-layer representation of the same k-th function, performed by the g-th agent.*

In the process of "identification of performance variability", the first phase consists of defining the phenotypes of variability (i.e. manifestations of variability). Even if it would be possible to adopt a large set of phenotypes, a simple solution consists of considering two of them: timing and precision (Hollnagel, 2012). In terms of timing an output occurs (e.g.) too early, on time, too late or even not at all. In terms of precision, the same output can be precise, acceptable, imprecise or wrong. For the semi-quantitative framework used in this research, it is necessary to assign a numeric score to functions' variability, based on the criticality of its variability state. Since functions' behaviour is not deterministic and static, it is necessary to define a probability distribution of potential states of variability, which corresponds to a distribution of scores. Under the assumption of independent states of variability for the two phenotypes, the variability of a function's output OV_j can be expressed as the product of two distributions: V_j^T, representing the score distribution in terms of timing, and V_j^P representing the score distribution in terms of precision, both for the j-th output. Monte Carlo simulation allows calculating OV_j, which is the distribution of variability for the j-th output (Output Variability) in terms of criticality:

$$OV_j = V_j^T \cdot V_j^P \qquad 1$$

For the "aggregation of variability" step, it is necessary to understand how the output's variability affects its upstream/downstream couplings. Following the connections described in the FRAM model, an output may relate to different functions, generating different effects depending on the output's variability (i.e. its score) and the specific aspect it is linked to (i.e. the upstream/downstream connection), as stated by the principle of functional resonance (Hollnagel, 2012). The upstream/downstream connection might generate an amplification or a damping effect, or can be negligible. On this path, the two indexes a_{ij}^T and a_{ij}^P represent the amplifying factor for the connection between the j-th upstream output and the i-th downstream function, respectively in terms of timing and precision. Their values can be exactly 1 in case of no functional resonant effect, greater than 1 in case of an amplifying effect, and minor than 1 for a damping effect. A probability distribution function CV_{ij} represents the Coupling Variability for the j-th upstream output and the i-th downstream function:

$$CV_{ij} = OV_j \cdot a_{ij}^T \cdot a_{ij}^P \qquad 2$$

Lastly, for the "management of variability" step, once a CV_{ij} is ascribed to each link in the model, it is possible to filter the couplings based on their values over a threshold CV^*. Once assigned a confidence level P^*, a coupling will be considered critical if CV_{ij}^*, i.e. the cumulative distribution of CV_{ij} over CV^*, is greater than $(1 - P^*)$. This classification helps ranking the couplings based on the cumulative distribution value over the threshold, in order to define mitigating actions for managing the negative effects of functional resonance. The scores, as well as the effects of performance variability and the definition of the threshold have to be determined based on available data and on the judgments of Subject Matter Experts (SMEs), who play a crucial role for the application of the described semi-quantitative framework.

3 ILLUSTRATIVE EXAMPLE

This section provides some indications about the application of the framework for a railway incident happened in November 2005 between Esher and Hampton Court Junction in UK. The event caused no injuries to people and no direct damage to the infrastructure, but it caused serious negative effects on the traffic of the track. The immediate cause described in the RAIB incident report was low adhesion on the up fast line, as a direct consequence of the presence of contaminants on the rail and no previous rail treatment (Rail Accident Investigation Branch, 2008). This paper summarizes the outcomes arising from the application of the FRAM semi-quantitative framework combined with the Abstraction/Agency framework. The work presented in this paper starts from a recently published research (Patriarca, Bergström, et al., 2017) that developed the Abstraction/Agency framework for the same incident, as an illustrative case study to explain the feature of the framework itself, without discussing the actual work domain.

The FRAM analysis started with the official RAIB report, used as a starting point to analyse procedures, standards, and other reports with similar low adhesion issues in UK. Note that the Esher incident was one of several adhesion-related events happened during the autumn of 2005 in UK. The focus group was made up of 5 people: two researchers with experience in FRAM modelling and an engineering background, one researcher with a background in railway engineering, two SMEs (one train driver and one railway signaller, both with 10+ years of work experience with similar trains). The analysis included in this paper does not aim to be a complete and exhaustive incident analysis; it rather aims at illustrating the potential benefits of a combined multi-layer semi-quantitative framework for FRAM. Figure 2 details the Abstraction/Agency framework, which includes 6 Agents, and 4 abstraction levels, whose meaning is discussed in (Patriarca et al., 2017a, p. 38).

Agency / Abstraction	AGENT 1 Industrial Committee for Standards	AGENT 2 Weather Forecast Company	AGENT 3 Infrastructure Company	AGENT 4 Signaller	AGENT 5 Train Company	AGENT 6 Driver
FUNCTIONAL PURPOSE (FP)	1 FP	1 FP	1 FP	1 FP	1 FP	1 FP
GENERALIZED FUNCTION (GF)	1 GF	1 GF	3 GF	5 GF	2 GF	8 GF
PHYSICAL FUNCTION (PF)	Not analysed	2 GF	17 PF	18 PF	Not analysed	29 PF
PHYSICAL AND TECHNOLO-GICAL FORM (PTF)	Not analysed	Not analysed	Not analysed	Not analysed	Not analysed	13 PTF

Figure 2. *Conceptual Abstraction/Agency framework developed for the analysis. The analysis focused mainly on the actions of the Driver, as proved by the interest in using the maximum levels of abstractions for its modelling, i.e. PTF (Patriarca, Bergström, et al., 2017).*

The framework helped organizing the FRAM functions by a structured representation to manage the complexity of representation with sensible benefits, if compared with traditional modelling (as observed by the two researchers in the focus group with experience in FRAM). As an outcome of the framework it has been possible to develop several intra-agent inter-level, intra-agent intra-level analyses, as theoretically described in (Patriarca, Bergström, et al., 2017). As a further development, the Monte Carlo framework, allowed performing systematically several of these analyses, with the purpose of extracting the more critical couplings, based on the effects of their variability. As a first step, as discussed in § 2.3, two phenotypes of variability have been identified, i.e. timing and precision, assigning then a score for each state, as detailed in Table 1. Then, each output of the model at the n_g-th abstraction level has been described in terms of its variability, relying on the analysis of other reports of similar train and infrastructure conditions and moreover on the experience of the SMEs involved in the focus group, who described their activities in everyday work. Since FRAM relies on normal work, work-as-done, the experience referred by the SMEs acquired a crucial role for defining the model and its inherent variability. For each output, by operational data (where available, e.g. meteo conditions) and the analysis of normal work in semi-structured interviews, $V_j^T, V_j^P, a_j^T, a_j^P$ have been assinged, following Table 1. At this step, the Abstraction/Agency framework has been explored by Monte Carlo simulation in order to understand and get indications on how to manage the variability of the process. A coupling has been considered critical if the CV_{ij}^* cumulative distribution over a threshold exceeded $CV^* = 8$, with a confidence level $P^* = 0.95$. The threshold $(CV^* = 8)$ can be interpreted to isolate those outputs whose variability has limited consequences on the process $(V_j^T = V_j^P = 2)$ but with a least an amplifying effect $a_j^T\left(or\ a_j^P\right) = 2$.

The Monte Carlo simulation has been applied for an inter-agent inter-level analysis for Agent 6, i.e. Driver at the abstraction level of Physical Functions (PFs). The variability on the retardation rate observation plays a crucial role with a very high value of the cumulative probaiblity voer the threshold $(CV_{ij}^* = 0.22)$, leading to activate the braking management functions (see Figure 3A). Furthermore, an inter-agent intra-level analysis has been applied to assess the interactions between the Driver's PFs and the Generalized Functions (GFs) performed by the other agents. In this case, the in-loco low-adhesion warning signals appear to have a crucial role $(CV_{ij}^* = 0.45)$ for Driver's awareness (see Figure 3B) and then preparedness to manage successfully abnormal adhesion conditions and braking actions (this coupling represents an example of an intra-level criticality).

Table 1. *Semi-quantitative parameters used in the Monte Carlo framework. $V_j^T, V_j^P, a_j^T, a_j^P$ are probability distribution functions defined by the corresponding values fo the variability state assigned in the analysis.*

V_j^T, V_j^P score	Criticality effect	a_j^T, a_j^P score	Criticality effect
1	The output variability has *no critical implications* on the process	**0.5**	The output has a *damping effect* on the variability of upstream/downstream coupling)
2	The output variability has *limited consequences* on the process	**1**	The output has *no effect* on the variability of upstream/downstream coupling)
3	The output variability has *relevant consequences* on the process	**2**	The output has an *amplifying effect* on the variability of upstream/downstream coupling)
4	The output variability has *dangerous consequences* on the process		

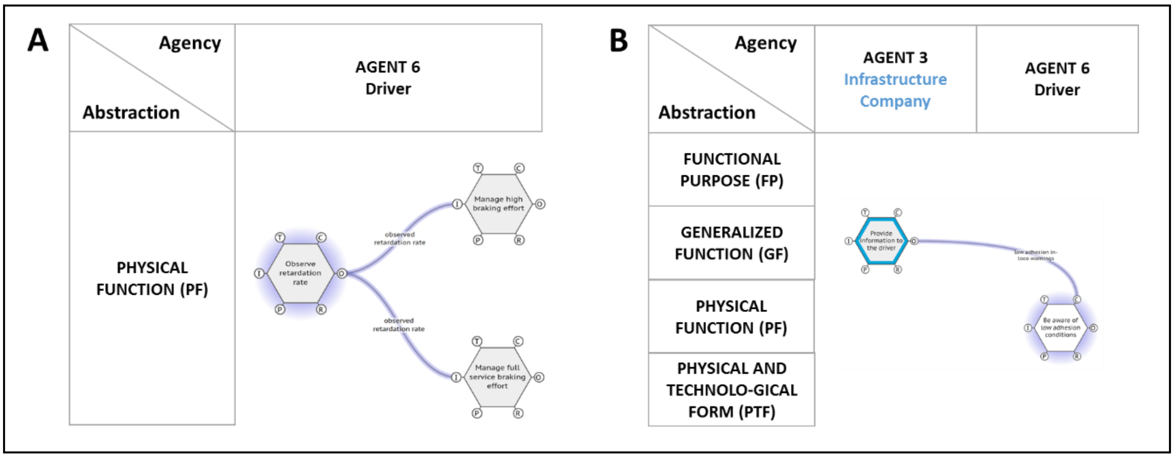

Figure 3. *Examples of critical couplings emerged from the Monte Carlo simulation applied to the Abstraction/Agency framework: A) coupling emerged from a semi-quantitative inter-agent inter-level analysis (at PF level); B) coupling emerged from an inter-agent intra-level analysis (between PF and GF levels).*

4 CONCLUSION

This paper shows how a traditional FRAM analysis can be combined with Monte Carlo simulation and with the Abstraction/Agency framework. The combined approach appears particularly relevant for systematic inter-agent inter-level, or inter-agent intra-level analysis, helping the analysts managing complexity by looking at the same model using different resolutions. The semi-quantitative approach allows filtering the complexity of representation, ranking the couplings' criticality. This results might be potentially helpful to develop more detailed monitoring indicators (sensors, specific questionnaires, reporting procedures, etc.) which can be used to gather real data and define proper mitigating actions (Albery, Borys, & Tepe, 2016), other than feeding the simulation model to refine the analysis. This purpose can be achieved starting from a detailed analysis of the more critical couplings, i.e. the ones with higher CV_{ij}^* (e.g., referring to Figure 3, discussing how to improve the in-loco warning signals, or performing an observational study to understand how in everyday work the observation of retardation rate is actually delayed).

The Abstraction/Agency framework allows developing a more comprehensible FRAM model, with potential implications for risk assessment and accident analysis, and even for organizational knowledge management. The Monte Carlo framework allows highlighting which sources of variability have to be damped, or enhanced, gaining a deeper knowledge of the process under analysis, helping decision-makers defining short-term and long-term actions to enhance safety and performance levels. A Monte Carlo multi-layer approach helps understanding system failure according to complexity theory, which prescribes “going up and out” to explore how functions are related at different abstraction levels with different agents (Dekker, 2011). The approaches described in this paper for illustrative purpose (with no pretension to be an exhaustive incident analysis) can be adapted in different socio-technical systems, for the analysis of both performance and safety parameters.

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