Riccardo Patriarca, Giulio Di Gravio, Francesco Costantino, A Monte Carlo evolution of the Functional Resonance Analysis Method (FRAM) to assess performance variability in complex systems, Safety Science, Volume 91, January 2017, Pages 49-60, ISSN 0925-7535, http://dx.doi.org/10.1016/j.ssci.2016.07.016.

A Monte Carlo evolution of the Functional Resonance Analysis Method (FRAM) to assess performance variability in complex systems

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Abstract

Modern trends of socio-technical systems analysis suggest the development of an integrated view on technological, human and organizational system components. The Air Traffic Management (ATM) system can be taken as an example of one of the most critical socio-technical system, deserving particular attention in managing operational risks and safety. In the ATM system environment, the traditional techniques of risk and safety assessment may become ineffective as they miss in identifying the interactions and couplings between the various functional aspects of the system itself: going over the technical analysis, it is necessary to consider the influences between human factors and organizational structure both in everyday work and in abnormal situations. One of the newly introduced methods for understanding these relations is the Functional Resonance Analysis Method (FRAM) which aims to define the couplings among functions in a dynamic way. This paper evolves the traditional FRAM, proposing an innovative semi-quantitative framework based on Monte Carlo simulation. Highlighting critical functions and critical links between functions, this contribution aims to facilitate the safety analysis, taking account of the system response to different operating conditions and different risk state. The paper presents a walk-through section with a general application to an ATM process.

Keywords: FRAM, Safety-II, safety assessment, resilience engineering, Monte Carlo.

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Introduction

Even though the progress in safety management made flying one of the safest way to travel (IATA, 2013), there is a strong consensus that safety in aviation is something that always need to be improved in order not to remain static or become inadequate at system developments. ICAO defines (ICAO, 2013) safety as "the state in which harm to persons or of property damage is reduced to, and maintained at or below, an acceptable level through a continuing process of hazard identification and risk management".

This definition complies with the traditional idea of safety as "a condition where nothing goes wrong or where the number of things that go wrong is acceptably small". Safety is then measured by the consequence of its absence rather than a quality itself (EUROCONTROL, 2009). These concepts lead risk governance and safety management to focus, with good reason, on what can go wrong and can lead to unwanted outcomes. Investigations generally relies on the historical approach of listing up adverse events experienced during an accident. These data allow to delve into the negative occurrences in order to propose interventions to eliminate their cause or to define mitigating actions to damp the effects.

This approach, the so-called Safety-I, considers that adverse events happen because something went wrong and ensures that it is possible to find and treat the causes, in line with the "*causality credo*". Several methods and models follow this belief, aiming at individuating the cause-effect link between events. In the Air Traffic Management (ATM) system, starting from the Domino model (Heinrich, 1931), the Reason Swiss Cheese Model (RSCM) (Reason, 1990) acquired a fundamental role and became the base of EUROCONTROL Safety Regulatory requirements (ESARRs) (EUROCONTROL, 2001). All these models promote a bimodal view of the activities, considering acceptable and unacceptable outcomes as two distinct and different modes of functioning: things go right because the system functions as it should and because people work as imagined, things go wrong because something failed. It is then possible to achieve safety only minimizing, or even blocking, the transition from normal to abnormal functioning. In summary, Safety-I, relies on the following assumptions (EUROCONTROL, 2009):

- Systems are decomposable and well-understood
- System functioning is bimodal
- Systems and places of work are well-designed and correctly maintained
- Procedures are comprehensive, complete and correct
- Operators behave as they are expected to and as they have been trained to

- Designers have foreseen every contingency and have provided the system with appropriate response capabilities

Although these conception paved the way to outstanding improvements in safety research, they seem to be ineffective for current needs. The ATM system's work conditions significantly changed over the past decades with a remarkable change in the air traffic volume. Furthermore, the Air Traffic Control (ATC) procedures' complexity dramatically increased, in order to satisfy the performance demand. Nevertheless, the development of technology itself and the IT software capacity determined a significant modification of organization structure, instruments, human activities and human machine interface (HMI). In addition, very few factors are independent from each other and subsequently isolating functions and analyzing them in a one-by-one strategy could be ineffective. Detailing system description is becoming an always more elaborate activity as systems may change before the description process is completed. Thus, only partial understanding of the principles of system functioning is possible. The ATM system, as well as many other present-day socio-technical systems in different industries (e.g. health care, nuclear power plants, space missions), are generally underspecified or intractable. This conditions fail to comply with Safety-I perspective, whose assumptions become inapplicable due to the large complexity and interdependencies among functions.

Safety-II aims to fill this gap, looking at intractable systems' needs. In particular, due to the impossibility of prescribing tasks and actions in every detail, performance must become flexible rather than rigid. This concept is in line with resilience awareness that individuals and organizations habitually adjust their performance to match current demands, resources and constraints in order to compensate the incompleteness of procedures and instructions (Hollnagel et al., 2011). On this path, following Safety-II, the definition of safety shifts to consider not only the adverse outcomes (as in Safety-I), but also positive and negative events, in order to achieve a holistic view of the system and in-depth understand its functioning. Safety-I aims to limit performance variability, Safety-II requires to manage it proactively, rather than simply constrained it. For this purpose, the system functioning is not considered bimodal, i.e. function or malfunction, but strictly related to everyday work and subsequent performance variability, which is the real source of success as well of failures, as shown in Figure 1.

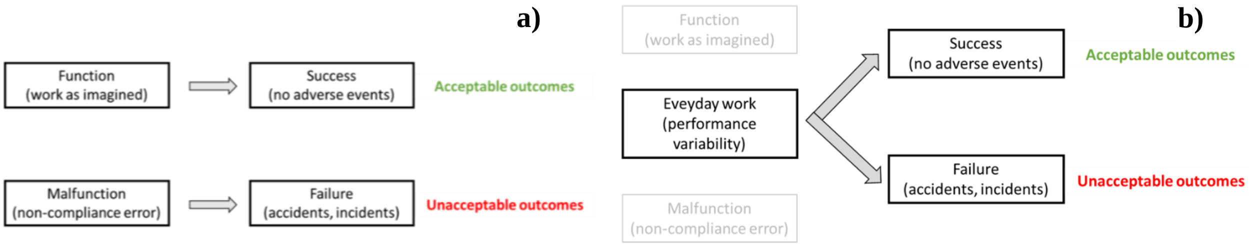

Figure 1. Different sources of success and failure: Safety-I (a) and Safety-II (b)

Safety-II characteristics summarize as follows:

- System components cannot be isolated in a meaningful way
- System functions are not bimodal but everyday performance is flexible and variable
- Human performance variability leads to success as well as failures
- Even though some outcome can be interpreted as a linear consequence of other events, some event result of coupled performance variability.

Since resilience refers (Caralli et al., 2006; Carlson et al., 2012; Wood et al., 2006) to something that an organization does (its ability to adjust the way things are done) rather than to something that an organization has (e.g. traffic count, number of accidents/incidents), it is difficult to measure it by counting specific outcomes, such as accidents or incidents.

FRAM (Hollnagel, 2012), as well as other methods (e.g.) STAMP (Leveson, 2004), RAG (Hollnagel, 2011), characterizes complex systems by their functions rather than by their physical structure. It enables capturing dynamics and interactions among functions by modeling non-linear dependencies and performance variability (Hollnagel, 2012). Based on Safety-II principles and traditional FRAM theory for risk assessment, this paper develops an evolution of the method into a semi-quantitative perspective, using a probabilistic approach based on Monte Carlo simulation to define critical functions. A walkthrough application to an ATM system process, i.e. the runway incursion, shows possible advantages and future developments.

The contribution of the paper are as follows. In the first section, it presents a wide literature on FRAM applications. The second section defines the FRAM principles and the FRAM model structure. Based on the FRAM traditional structure, the third section describes the evolution of the method. The fourth explains how to apply the method and validate the results of the analysis. Finally, the conclusions envisage the importance of this semi-quantitative method to assess risk and safety proactively, illustrating the possibility of further research.

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1 The FRAM in literature

The main FRAM applications mostly refer to the aviation context. One of the first (Sawaragi et al., 2006) systematically analyzes the automation effects under variable conditions of the pilot cabin. The study aims at understanding any collapses in operating procedures. In particular, the study focuses on the plane crash occurred in Colombia in 1995, flight 965, caused by the dis-coordination between the human and the automated aircraft. Nouvel et al. (2007) conduct an accident analysis about the MD83 aircraft approaching to the Paris Orly airport (ORY) in 23 November 1997. FRAM shows the difference in current risk state perception among the crew, cockpit and ground sector, modeling these interdependent links. With similar targets, Hollnagel et al. (2008) analyze the Comair Airlines flight 5191 accident happened the 27 august 2006 in Lexington (KY) and De Carvalho (2011) focuses on the accident between Gol Transportes Aéreos flight 1907 and an Embraer Legacy 600 in the airspace over the Amazon rainforest. Herrera et al. (2010) use FRAM instantiations in order to define safety performance indicators for Norwegian offshore helicopter traffic.

In the following years FRAM proved itself applicable also in several different industries and organizations, adapting to either small or large structures. Lundblad and Speziali (2008) apply FRAM in a nuclear power plant, to qualitatively assess risks in lifting fuel container of 60-80 tons, in order to propose recommendations at different organizational levels. Sujan and Felici (2012) propose FRAM as a complimentary method to FMEA to assess risks in the healthcare industry, considering socio-technical hazards. They conducted both FMEA and FRAM analysis of an emergency care pathway, showing the difficulty of assessing the worst credible consequences. Shirali et al. (2013) identify successfully the emergent risks by means of FRAM in a process unit of an oil refinery in Iran. Pereira (2013) apply FRAM to assess risks of a radiopharmaceutical dispatches process, highlighting how simple tasks may be combined in critical situations, which could lead to major undesirable consequences. Woltjer et al. (2007) show the emergency management effects in two micro-worlds, i.e. simulated task environments that capture critical aspects of a decision-making problem. In detail, they discuss the fire-fighting C3Fire and a dynamic wargame for experiments (DKE). Both the studies show the good outcomes of applying FRAM to model the command and control actions.

Two contribution shows the benefits arising from FRAM when applied in security analysis. Steen and Aven (2011) analyze the effects of potential cyber-attacks on railway, considering a scenario where the railway control system is exposed to an internet attack, causing a collision between two trains. They acknowledge the importance of FRAM to perform an effective systemic risk analysis. Belmonte et al. (2011) show the benefits deriving from adopting FRAM, even with respect to the traditional security analysis models, for rail traffic supported by the modern systems of Automatic Train Supervision (ATS).

One of the most recent research streams propose the adoption of FRAM to describe the differences between the work-as-done and the work-as-imagined, basing on the principle of local rationality. Clay-Williams et al. (2015) show the benefits for the implementation of new guidelines to reconcile the differences between work-as-imagined and work-as-done. They proved that using FRAM can reduce the need for clinicians to adjust performance and create alternative solutions, minimizing the effects on safety and quality. Praetorius et al. (2015) firstly categorize and sort datasets, using grounded theory on Vessel Traffic Service (VTS) systems, and then develop an everyday operation FRAM model of two distinct VTS systems looking at a work-as-done perspective. Amorim and Pereira (2015) apply FRAM to three different accidents deriving from people improvisation at work. The study shows the possibility that improvisation, i.e. performance variability, allows emerging resonant situations, which could lead to serious accidents.

Although these applications mainly differ in terms of research contexts, they all adopt FRAM as a qualitative method for assessing performance variability. However, several researchers recently explore the possibility of developing some quantitative evolution to the original FRAM.

Saurin and Sanches (2014) compare the Value Stream Mapping (VSM) and the FRAM for describing systems and identifying variability. This study explores the quantitative aspects of VSM and shows how FRAM still requires a structured quantitative approach. Rosa et al. (2015) suggests a FRAM evolution, using the Analytic Hierarchic Process (AHP), to reduce subjectivity in the definition process of performance variability phenotypes, required to describe the system through Subject Matter Experts (SME)' judgments.

Considering these relevant outcomes of the literature, this paper aims to provide a structured and user-friendly semi-quantitative evolution of FRAM, which will enhance the traditional risk assessment methods, allowing understanding the importance of tight and not easy detectable couplings and interactions. This approach aims to define the critical paths of functions which could lead to major accidents, according to a probabilistic evaluation of the performance variability of each function. Once individuated the critical functions, the FRAM could help defining the most appropriate mitigating actions to manage this variability and reduce risks.

2 The FRAM structure

Firstly Hollnagel (2004) proposes FRAM as a risk assessment and accident analysis method. After some updates from the original meaning, Hollnagel (2012) develops the current formulation, according to four principles:

- Equivalence of failures and successes. Failures and successes come from the same origin, i.e. everyday work variability. This latter allows both things go right, working as they should and things go wrong.
- Principle of approximate adjustments. People as individuals or as a group and organizations adjust their everyday performance to match the partly intractable and underspecified working conditions of the large-scale socio-technical systems.
- Principle of emergence. It is not possible to identify the causes of any specific safety event. Many events appear to be emergent rather than resultant from a specific combination of fixed conditions. Some events emerge due to particular combination of time and space conditions, which could be transient, not leaving any traces.
- Functional resonance. The function resonance represents the detectable signal emerging from the unintended interaction of the everyday variability of multiple signals. This resonance is not completely stochastic, because the signals variability is not completely random but it is subject to certain regularities, i.e. recognizable short-cuts or heuristic, that characterize different types of functions.

The following paragraphs presents the four steps to perform a FRAM analysis. However, in the so-called Step 0, it is necessary to make clear whether the analysis is an accident investigation or a risk assessment. While an accident analysis relies on data directly gathered from the events, it is generally difficult to identify what should have happened rather than what did happen. In risk assessment, decision maker are forced to consider that socio-technical system usually respond to external events differently and then to analyze the system behavior with respect to the whole function variability.

2.1 Step 1: Identification and description of system's functions

FRAM asks to analyze the functions enabling everyday work to succeed, evolving the Standard Analysis and Design Technique (SADT). A function represents the activities required to produce a certain outcome. Six different aspects can characterize each function:

- Input (I): what starts the function or what is processed or transformed by the function.
- Output (O): the result of the function, it can be either an entity or a state change and serves as input to the downstream functions.

- Precondition (P): mandatory conditions that must exist before carrying out the function. Preconditions do not necessarily imply the function execution.
- Resource (R): what the function needs when it is carried out or consumes to produce the output.
- Control (C): what controls and monitors the function, regulating its performance to match the desired Output.
- Time (T): temporal requirements or constraints of the function, with regard to both duration and time of execution.

Functions aims to describe daily system work, rather than the individual activities. The six aspects are traditionally at the corners of a hexagon, which represent the function itself (see Figure 2).

It is possible to divide functions into two classes: foreground and background. The foreground functions represent the core of the analysis, requiring a complete definition of all the six aspects, when possible. The background functions represent the components not in scope of analysis and therefore they need only one input or one output.

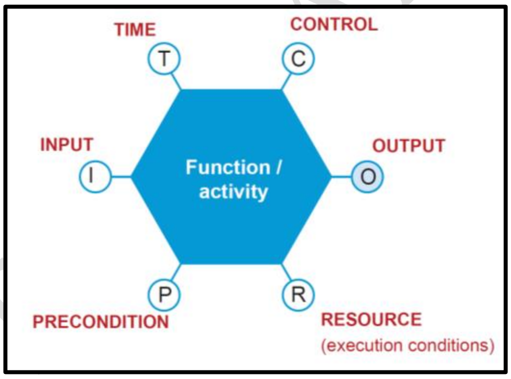

Figure 2. Graphical representation of a FRAM function

2.2 Step 2: Identification of performance variability

In the second step, it is necessary to characterize each function with potential and actual performance variability. This identification process must take into account both daily and abnormal variability and, especially, the output variability.

Over the last years, researchers propose different ways to characterize the function variability, with different variability manifestation, the phenotypes: from the simple solution considering only two phenotypes, i.e. timing and precision, to the more elaborate ones adopting multiple phenotypes, i.e. speed, distance, sequence, object, force, duration, direction, timing (Hollnagel, 2012). Note that this paper will evaluate the original configuration, only identifying time and precision as phenotypes as they are able to describe most consequences. A natural extension to the other phenotypes, even if it could refine the analysis, does not affect the general validity of the method.

2.3 Step 3: Aggregation of variability

The FRAM represents the potential couplings among functions, not showing the effects of a specific scenario. This step focus instead on examining specific instantiations of the model to understand how the potential variability of each function can become resonant, leading to unexpected results, as stated by the functional resonance process. It is therefore necessary to identify the functional upstream-downstream couplings. The variability of a function results as a combination of the function variability itself and the variability deriving from the outputs of the upstream functions, depending on the function type and the linked aspects type. This paper deals in detail with this step, improving the possibility to aggregate the variability, even with respect to the damping effects of each function.

2.4 Step 4: Management of variability

This last step consists of monitoring and managing the performance variability, identified by the functional resonance in the previous steps. Performance variability can lead both to positive and negative outcomes. The most fruitful strategy consists of amplifying the positive effects, i.e. facilitating their happening without losing control of the activities, and damping the negative effects, eliminating and preventing their happening. The dampening process may require substantial changes, even in a permanent way, involving people, organization or equipment preventing things from going wrong as well as contributing to things going right. In a more traditional way, it helps creating barriers and defenses to prevent from harmful situations (Hollnagel, 2012). Once identified the critical areas, FRAM proposes to define performance indicators to monitor ongoing processes and developments.

3 A semi-quantitative approach to FRAM

Hollnagel (2012) simplifies the definition of functions variability identifying three types of functions, following the technology-human-organization classification. In this case, it is possible to define the potential variability as dependent on the function type, implying that all the Technological (or Human or Organizational) functions have assigned the same variability. In a real case scenario, beyond this simplification, it would be necessary to have different values for these functions, in line with their real variability. This paper considers the variability definition on a one-by-one basis, just generalizing the function classification. The following sections aim at detailing the evolutions of the method, with respect to the FRAM steps in § 2.

3.1 Evolving FRAM step 2: Quantifying function variability

According to the definitions in § 2.2, an output can be defined by timing and precision. In terms of timing, an output can occur *too early*, *on time*, *too late* or *not at all*. "Not at all" represents the possibility that an output is so late to be useless for its purposes or even not produced at all. In terms of precision, an output can be *precise*, *acceptable* or *imprecise*. If the output is precise, it satisfies entirely the needs and requirements of its downstream function. If it is acceptable, it requires some adjustment in the downstream function, even bigger in case it is imprecise. A fourth category, *wrong*, represents an output completely different from the expected one. In this case, rather than adjustments, the downstream function requires improvisation, amplifying the function variability.

It is then possible to assign a numerical score to each performance variability state, rather than describing a function by a linguistic definition. A rating scale can express the effects on performance of a function variability: the higher the score, the more variable the output. Experiences from the field can help to define the linguistic and the numerical scores according to the specific process performance. The variability of the upstream output j, OV_j is the product of these two scores (1):

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

where:

V_j^T represents the upstream output j score in terms of timing

V_j^P represents the upstream output j score in terms of precision

3.2 Evolving FRAM step 3: Aggregating the performance variability

Upstream functions affect the variability of a downstream function depending on their characteristics and the type of link.

3.2.1 Damping and amplification

For any generic function, it is possible to qualitatively define the effects of a coupling in terms of variability. For example, an upstream output that represents a precondition for the downstream function may cause a loss of time if it arrives too late, amplifying the variability. On the other hand, the same output may damp the variability, if on time, or may result in a false start and amplify variability, if too early. Also in terms of precision, the same output may cause misunderstanding and amplify variability, if imprecise or even it may cause a loss of time to eliminate potential disambiguation, if wrong. Even though some typical behaviors for specific couplings are common, as shown in Chapter 7 of Hollnagel (2012), an accurate analysis has to evaluate the effect of each specific coupling on its own. These qualitative evaluations can evolve into a semi-quantitative

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evaluation. In line with (1), a specific index for timing and precision can represent the damping or amplifying effects of each coupling, defining the coupling variability of the upstream output j and the downstream function i, as (2):

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

Where:

a_{ij}^T represents the amplifying factor for the upstream output j and the downstream function i, in terms of timing

a_{ij}^P represents the amplifying factor for the upstream output j and the downstream function i, in terms of precision

Note that a_{ij}^T (or a_{ij}^P) may assume the following values:

$$a_{ij}^T (\text{or } a_{ij}^P) \begin{cases} > 1 & \text{in case the upstream output has an amplyfing effect on the downstream function} \\ = 1 & \text{in case the upstream output has no effect on the downstream function} \\ < 1 & \text{in case the upstream output has a damping effect on the downstream function} \end{cases} \qquad 3$$

3.2.2 Different instantiations

Once defined the functions and their couplings effect on variability, it is necessary to consider how the operating scenario affects the process and everyday work. For example, in the ATM system, it is common to consider specific characteristics as for the meteorological conditions, the Air Traffic Controller (ATCO) workload, the traffic level of the airspace, the training level of human resources, etc.

In order to consider a particular instantiation of the model, it is to define a specific number m of variables, capable of identifying the scenarios to analyze, i.e. Scenario Performance Conditions SPC^k, where $k = 1, \dots, m$, and their potential effect. For example, looking at the ATM system, an intense traffic level has a high impact on the ATCO activities, a low impact on the instrumental communication functioning and even no impact on the meteorological radar. It is thus possible to build the Scenario Performance Condition Impact (SCPI) matrix, which identifies the impact of each SPC^k for each function, as shown in Table 1.

Table 1. Scenario Performance Condition Impact (SPCI) generic matrix.

	SPC^1	SPC^2	…	SPC^m
Function 1	b_1^1	b_1^2		b_1^m

Function 2	b_2^1	b_2^2		b_2^m
…				
Function n	b_n^1	b_n^2		b_n^m

Where:

b_j^k identifies the effect of the SPC^k on the j function. Note that b_j^k may assume the following values (4):

$$b_j^k \begin{cases} = 1 & \text{in case the } SPC^k \text{ has a high impact on the j function} \\ < 1 & \text{in case the } SPC^k \text{ has a moderate impact on the j function} \\ = 0 & \text{in case the } SPC^k \text{ has no impact on the j function} \end{cases} \quad 4$$

A particular combination of SPC^k constitutes an operating scenario. It is possible to build the S matrix, which relates each scenario to the identified SPC^k, by the SPC_z^k. SPC_z^k represents the SPC^k amplifying effect in the z scenario S_z, $z = 1, \ldots, Z$, as shown in Table 2.

Table 2. Scenario (S) generic matrix.

	$\boldsymbol{SPC^1}$	$\boldsymbol{SPC^2}$	…	$\boldsymbol{SPC^m}$
Scenario 1	SPC_1^1	SPC_1^2		SPC_1^m
Scenario 2	SPC_2^1	SPC_2^2		SPC_2^m
…				
Scenario Z	SPC_Z^1	SPC_Z^2		SPC_Z^m

Where SPC_z^k rating scale has the same extreme values defined in (5), in order to verify mathematical coherence:

$$SPC_z^k = \begin{cases} SPC_z^{k'} & \text{High Variability effect of SPC}^k \\ SPC_z^{k''} & \text{Low Variability effect of SPC}^k \\ SPC_z^{k'''} & \text{No Variability effect of SPC}^k \end{cases} \quad 5$$

At this step, the conditional variability $\boldsymbol{e_j^z}$ of any output $\boldsymbol{j}$, due to the operating conditions state in a particular scenario $\boldsymbol{z}$ is (6):

$$e_j^z = \frac{\sum_{k=1}^{m} SPC_z^k \cdot b_j^k}{m} \quad 6$$

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This equation has to be formally modified to consider that a function j may be not influenced by any SPC^k, i.e. $b_j^k = 0$ for each k. In this case $e_j^z = 1$, confirming that the scenario does not amplify the function variability

$$e_j^z = max\left\{1; \frac{\sum_{k=1}^{m} SPC_z^k \cdot b_j^k}{m}\right\} \qquad 7$$

The overall index for each coupling, which address its variability according timing and precision phenotypes, in an operating scenario z can be derived as (8):

$$VPN_{ij}^z = V_j^T \cdot V_j^P \cdot a_{ij}^T \cdot a_{ij}^P \cdot e_j^z \qquad 8$$

One of the main issues in defining the scores for each function arises from the awareness that a static behavior for a system component may not perfectly reflect a real case. For example, even though an instrument output is generally precise and on time, it may have rare unpredictable errors and delays on transmissions, resulting in an imprecise and/or too late output. This factor plays an even more important role in case of organizational or human functions where a static variability score level is inappropriate or even wrong. For this purpose, it is possible to adopt discrete probability distribution functions to more properly define the function variability. Each function has its own discrete probability distribution, in terms of V_j^T and V_j^P, as shown (e.g.) in Figure 3 and Figure 4.

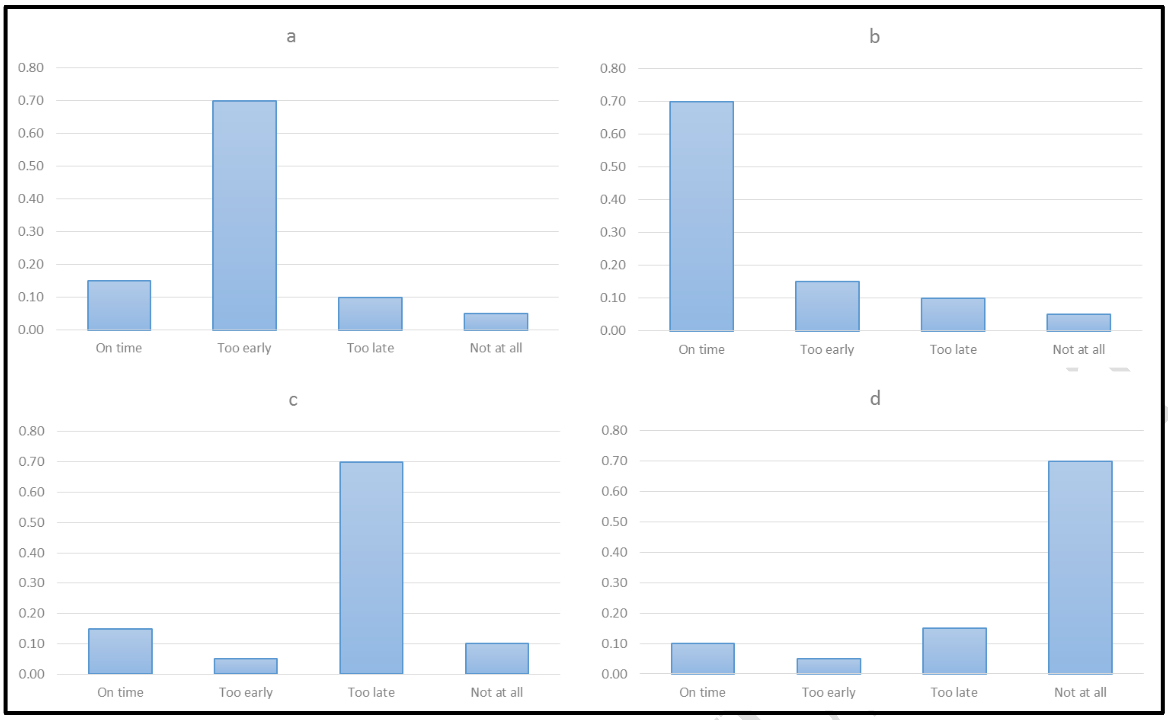

Figure 3. Some example of adoptable probability distribution functions for the timing variability.

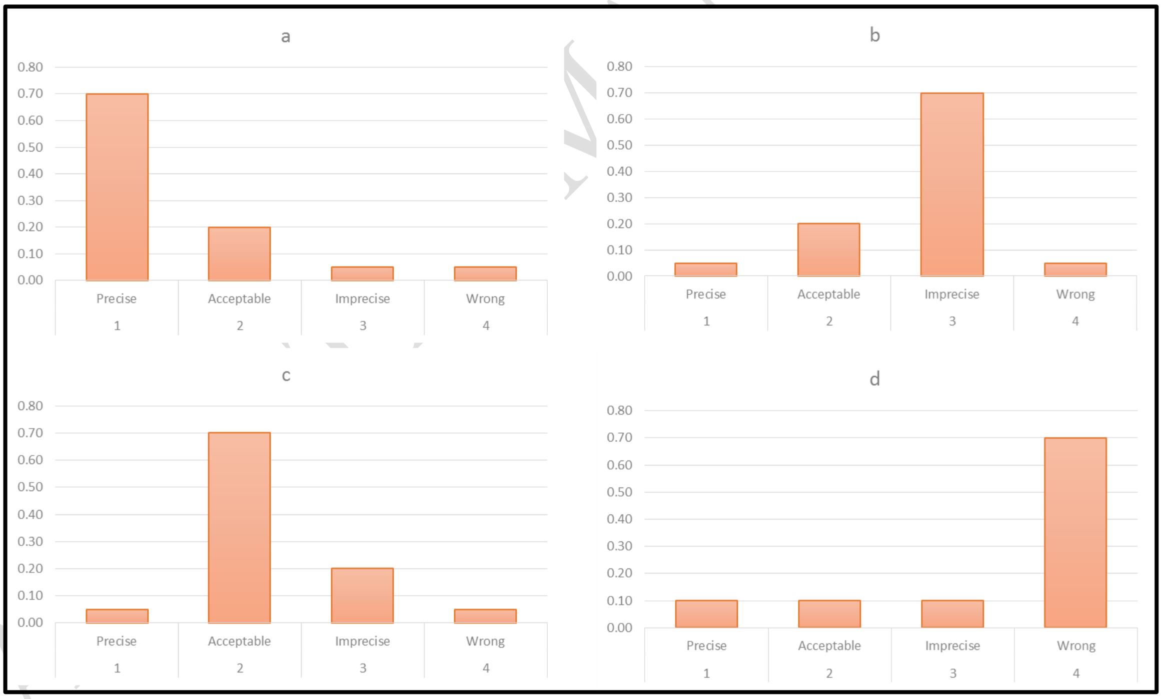

Figure 4. Some example of adoptable probability distribution functions for the precision variability.

Through Monte Carlo simulation, the product in (8) becomes a discrete probability distribution as well, propagating the uncertainties in V_j^T and V_j^P into uncertainties in VPN_{ij}^z. Dunn and Shultis (2011) prove the grounded application of Monte Carlo methods in several fields. For the ATM system, Stroeve et al. (2009) applied Monte Carlo method to validate the effects of action on runway incursions events. Jacquemart and Morio (2013) developed a Monte Carlo simulation to estimate conflict probability between aircrafts and Di Gravio et al. (2015b) show the benefit of Monte Carlo simulation in the definition of proactive safety indicators.

3.3 Evolving Step 4: Monitoring and managing the variability

The evolved step 3 defines the variability of each coupling taking into account the upstream variability, the upstream-downstream links and the operating scenario. Fixing a threshold VPN^* and a confidence level P^*, it is possible to define critical all the couplings whose cumulative distribution under the threshold is minor than the confidence level.

In order to help the decision-maker at individuating the appropriate mitigating actions, rather than simple independent critical couplings, it is possible to define critical paths as a chain of backwards or afterwards critical couplings which relate the same functions. The functional resonance emerges relating multiple critical upstream-downstream functions. This analysis defines the priority of intervention, addressing the investigation to start from the most critical elements.

4 Walkthrough application

ATM is a socio-technical system which perfectly fits with the Safety-II perspective: tight and loose couplings between human (e.g. ATCO, pilots, maintenance operators), organizational (e.g. operating procedure, sector-to-sector communication procedures, flight planning, NOTAMs) and technological (e.g. radars, automatic dependent surveillance, computer and IT systems, communication devices, automatic navigation and approach systems, traffic alert and collision avoidance system) factors guarantee its safe functioning. During daily airport operations, therefore, a little oversight, a short communication breakdown or even imperfect procedures can cause minor issues, incidents or even accidents. One of the most critical safety events for the airport operations is the runway incursion (RIN). ICAO (2007) defines a runway incursion any occurrence at an aerodrome involving the incorrect presence of an aircraft, vehicle or person on the protected area of a surface designated for the landing and take-off of aircrafts. Such events have lead also to many deaths as in the Taipei SQ B744 accident. This general application aims to show how everyday activities may lead to a runway incursion, adopting a semi-quantitative FRAM. The analysis takes in charge the ATM system, following the Air Navigation Service Provider (ANSP) perspective. The ATM aims to safely and efficiently control air traffic in normal as well as uncommon conditions. The goal of this study consists of identifying the critical functions, in normal and abnormal operating conditions. To this extent, a pool of three Subject Matter Experts (SMEs) cooperated to link the theoretical aspects of the model with their experience on the field, specifying the quantitative values for each weight.

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4.1 Step 1: ATM functions related to Runway Incursion

The first step consists of identifying the interacting functions, describing them and finding how they interact, defining thus the couplings, as shown in Figure 5, where the grey hexagons indicate the background functions. Note that in the figure there is not a specific "runway incursion" function but several functions which express system functions potentially leading to it (start taxing, start take-off, start landing, start crossing). Table 3 provides a short description of each function.

Table 3. FRAM function descriptions.

FUNCTION	DESCRIPTION
MET radar functioning	Providing meteorological radar data to ATCO
ADS-B functioning	Providing ADS-B data to ATCO
NOTAM functioning	Providing information to alert aircraft pilots of potential hazards
Communication Pilot/ATCO instruments functioning	Communication link between pilot and ATCO
Absence of undesired obstacles on APT surface	Keeping APT surface clear of obstacles and providing timely information when it is not possible
Static Visual Aid	Static aid in the APT: signage and marking
Cockpit alert advisory	Providing alert signal to pilot, enabled either remotely or automatically
Monitoring	Monitoring to anticipate traffic development
Planning	Developing a control plan to anticipate conflicts and manage traffic flow
Coordination	Coordinating with adjacent sectors for flight level, vectoring, route, etc.
Display data at Controller Working Position	Displaying data on ATCO working position
Sector-sector communication	Communicating between adjacent sectors
Manage APT lights	Ensuring efficient working aids on the airport
Strip marking	Marking the issued clearances by specific strips
Issue taxi clearance to pilot	Issuing taxi clearances to pilots
Issue take-off clearance to pilot	Issuing take-off clearances to pilots
Issue landing clearance to pilot	Issuing landing clearances to pilots
Issue crossing clearance	Issuing crossing clearances
Pilot/ATCO communication	Communication initiated by pilots, to establish radio contact or to request clearances by ATCO
Pilot Situational awareness	Pilot awareness of current airspace situation
Start taxing	Pilot executes taxing procedures
Start take-off	Pilot executes take-off procedures

Start landing	Pilot executes landing procedures
Start crossing	Pilot executes crossing an intersection or RWY

Considering the aim of the study, the system is described with a small set of high level functions to highlight the main couplings to further investigate and, at the same time, reduce the computational effort of the Monte Carlo simulation. These assumptions don't affect the validity of the method and help to simply show the possible results and advantages.

4.2 Step 2: Identification of performance variability for the ATM system

The SMEs assign the scores to each variability, as shown in Table 4, and define the discrete probability distribution for each system function, as shown in Table 5 and Table 6.

Table 4. Variability score with respect to time and precision

	VARIABILITY	SCORE
TIMING	On time	1
	Too early	2
	Too late	3
	Not at all	4
PRECISION	Precise	1
	Acceptable	2
	Imprecise	3
	Wrong	4

Table 5. Variability score according to timing.

	1	**2**	**3**	**4**
Probability of being Too early	0.15	0.70	0.10	0.05
Probability of being On time	0.70	0.15	0.10	0.05
Probability of being Too late	0.15	0.05	0.70	0.10
Probability of Not at all	0.10	0.05	0.15	0.70

Table 6. Variability score according to precision.

	1	**2**	**3**	**4**
Probability of being Precise	0.70	0.20	0.05	0.05
Probability of being Acceptable	0.05	0.70	0.20	0.05
Probability of being Imprecise	0.05	0.20	0.70	0.05
Probability of being Wrong	0.10	0.10	0.10	0.70

Riccardo Patriarca, Giulio Di Gravio, Francesco Costantino, A Monte Carlo evolution of the Functional Resonance Analysis Method (FRAM) to assess performance variability in complex systems, Safety Science, Volume 91, January 2017, Pages 49-60, ISSN 0925-7535, http://dx.doi.org/10.1016/j.ssci.2016.07.016.

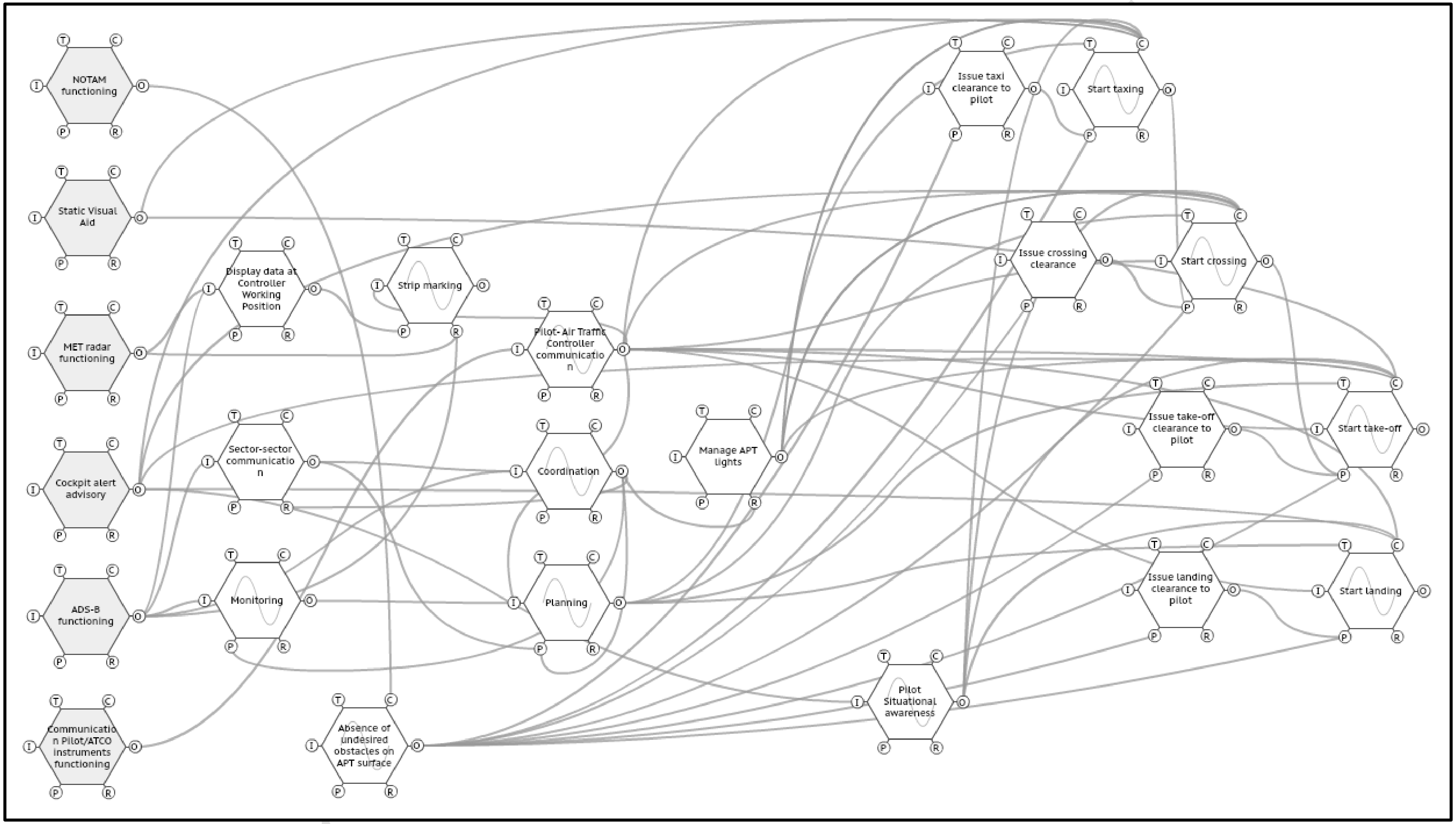

Figure 5. FRAM map for runway incursion.

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4.3 Step 3: Aggregating the performance variability quantitatively for the ATM system

Once assigned the variability score, the SMEs assign also the amplifying factors a_{ij}^T and a_{ij}^P (9), specifying (3):

$$a_{ij}^T(\text{or } a_{ij}^P) = \begin{cases} 2 & \text{in case the upstream output has an amplyfing effect on the downstream function} \\ 1 & \text{in case the upstream output has no effect on the downstream function} \\ 0.5 & \text{in case the upstream output has a damping effect on the downstream function} \end{cases} \qquad 9$$

The SMEs assign then b_j^k(10), specifying (4) and SPC_z^k(11), specifying (5)

$$b_j^k = \begin{cases} 1 & \text{in case the } SPC^k \text{ has a high impact on the j function} \\ 0.5 & \text{in case the } SPC^k \text{ has a moderate impact on the j function} \\ 0 & \text{in case the } SPC^k \text{ has no impact on the j function} \end{cases} \qquad 10$$

$$SPC_z^k = \begin{cases} 4 & \text{High Variability effect of SPC}^k \\ 2 & \text{Low Variability effect of SPC}^k \\ 1 & \text{No Variability effect of SPC}^k \end{cases} \qquad 11$$

Table 7 shows an example of the amplifying factors applied to the score probability distribution function of two system functions.

About system scenarios, in the ATM context several aspects have a relevant impact on system performance. In particular, the ATM system may interface with different external condition, including the possibility of airspace sectorization, the presence of military operation areas, the traffic volume, and the meteorological conditions. Then, it is necessary to consider the organization operating level, evaluating the ATM procedure state, the frequency of their change, the difficulties arising from implementing them, the training level and the resource availability. At human level, the ATCO condition has a crucial role. The analysis has to consider also the ATCO experience, workload, physical and physiological condition, circadian rhythm, etc.

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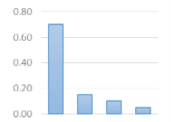
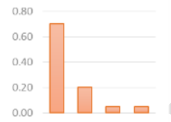
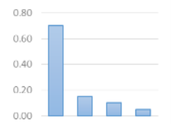
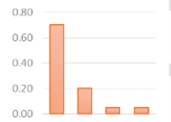
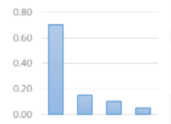
Table 7. Amplifying factors example.

Downstream function		**Upstream function**				**Amplifying factor**	
Name of function	**Aspect**	**Name of function**	**Description of Aspect**	V_j^T	V_j^P	a_{ij}^T	a_{ij}^P
Absence of undesired obstacles on APT surface	Control	NOTAM functioning	NOTAM issued			1	0.5
Sector-sector communication	Input	ADS-B functioning	ADS-B data			1	0.5
	Resource	Coordination	Coordinated personnel			0.5	2

In a general perspective, it is then possible to summarize these aspects considering three SPC , which are respectively the complexity level of airspace (CLA), the organization condition (ORG), the ATCO condition (HCO). In addition, the analysis considers a fourth SPC: the disruption effects (DIS). This latter is related to external, unpredictable events which can lead to critical performance variability, (e.g.) earthquake, blackout, hijack. Table 8 defines the impact of each SPC on the functions, considering (4).

Table 8. Scenario Performance Condition Impact (SPCI) in the ATM context for a RIN.

Function	SPC^1	SPC^2	SPC^3	SPC^4
	CLA	HCO	ORG	DIS
MET radar functioning	1	0	0	1
ADS-B functioning	0.5	0	0	1
NOTAM functioning	1	0	1	1
Communication Pilot/ATCO instruments functioning	0.5	1	0	1
Absence of undesired obstacles on APT surface	0	0.5	1	1
Static Visual Aid	1	0	0	1
Cockpit alert advisory	0	0	0	1
Monitoring	0.5	1	1	0.5
Planning	0.5	1	1	0.5
Coordination	1	1	1	0.5

Display data at Controller Working Position	0	0	0	1
Sector-sector communication	1	1	1	0.5
Manage APT lights	0	0	0.5	1
Strip marking	1	1	0.5	1
Issue taxi clearance to pilot	0.5	1	0	0.5
Issue take-off clearance to pilot	0.5	1	0	0.5
Issue landing clearance to pilot	0.5	1	0	0.5
Issue crossing clearance	0.5	1	0	0.5
Pilot/ATCO communication	1	1	0.5	1
Pilot Situational awareness	1	0.5	0	0.5
Start taxing	0	0	0.5	0
Start take-off	0	0	0.5	0.5
Start landing	0	0	0.5	0.5
Start crossing	0	0	0.5	0.5

Rather than considering all the possible combinations of these four SPC, this analysis focuses on six different scenarios, assigning some conditions. In detail, fixing a medium variability level due to CLA ($SPC_z^1 = 2$), a low variability level due to ORG ($SPC_z^3 = 1$), the analysis considers a situation with no variability ($SPC_z^4 = 1$) and critical variability ($SPC_z^4 = 4$) due to DIS, with respect to any HCO ($SPC_1^2 = SPC_4^2 = 1, SPC_2^2 = SPC_5^2 = 2, SPC_3^2 = SPC_6^2 = 4$), as summarized in Table 9.

Table 9. Scenario considered in the analysis.

Scenarios	$\boldsymbol{SPC^1}$	$\boldsymbol{SPC^2}$	$\boldsymbol{SPC^3}$	$\boldsymbol{SPC^4}$
	CLA	HCO	ORG	DIS
Scenario 1	2	1	1	1
Scenario 2	2	2	1	1
Scenario 3	2	4	1	1
Scenario 4	2	1	1	4
Scenario 5	2	2	1	4
Scenario 6	2	4	1	4

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Figure 6 presents an example of the resulting distribution of VPN_{ij}^{z}, for the coupling "NOTAM issued" between the functions "Absence of undesired obstacles on APT surface" and "NOTAM functioning" shown in the first row of Table 7, respectively in Scenario 1 (VPN_{ij}^{1}) and Scenario 6 (VPN_{ij}^{6}).

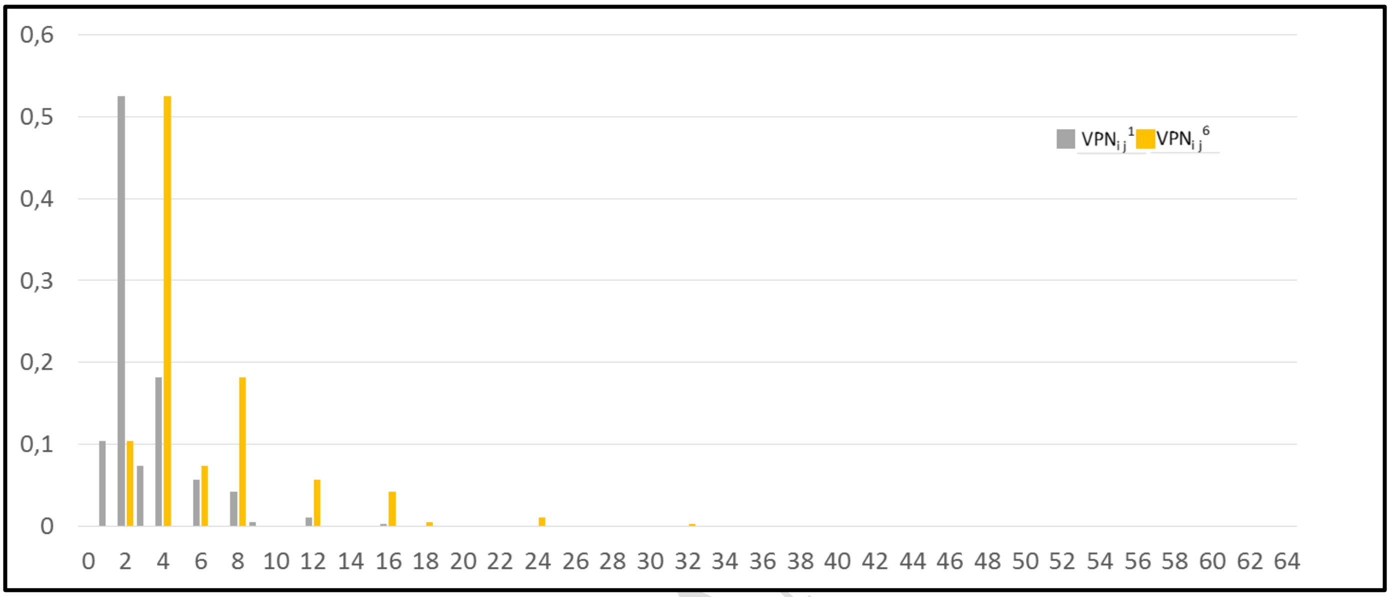

Figure 6. An example of VPN_{ij}^{z}, obtained by Monte Carlo simulation.

4.4 Step 4: Monitoring and managing the variability in the ATM context

To rank the critical couplings, the first operative stage consists of defining the variability threshold. In this context, it seems meaningful to define a situation critical (e.g.) if the upstream output is too late, with amplification factor, and acceptable in a scenario causing a medium variability amplification. Considering other combinations of these factors, the minimum threshold is $VPN^{*} = 24$, assigning a 95% confidence level on 1000 Monte Carlo iterations. The analysis considers a coupling critical if the cumulative distribution of VPN_{ij}^{z} over 24 is major than 0.05, as shown in some example in Table 10. Note how the functions suffer differently the scenario variability (*system resilience*).

Table 10. Scenarios structure example.

Downstream function		Upstream function		Scenarios					
Name of function	**Aspect**	**Name of function**	**Description of Aspect**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Scenario 6**
Absence of undesired obstacles on APT surface	Control	NOTAM functioning	NOTAM issued	0	0	0	0	0.004	0.004
Sector-sector communication	Input	ADS-B functioning	ADS-B data	0	0	0	0	0.004	0.004
	Resource	Coordination	Coordinated personnel	0	0.001	0.001	0.001	0.001	0.001
Pilot/ATCO communication	Input	Communication Pilot/ATCO instruments functioning	Pilot/ATCO communication link active	0	0.001	0.001	0.158	0.158	0.158
Start crossing	Input	Pilot/ATCO communication	Clarified instructions	0	0.275	0.275	0.275	0.275	0.770

Once individuated the critical couplings, it is to observe as they interact and create resonant paths, i.e. three or more functions, linked by two or more critical couplings. Figure 7 shows a critical path in Scenario 1, in which the function Pilot/ATCO communication plays a main role. Figure 8 shows the same path, in case of abnormal external conditions, i.e. Scenario 6. In case of variability increased due to external conditions, the functional resonance involves other functions, which highlights other potential sources of variability. In case of disruption, also communication instruments can lead to imprecise outcome and then the coordination for planning the operations may have a relevant impact.

The outcome of the analysis, as shown in Figure 7 and Figure 8, envisages the crucial role of communication between Pilot and ATCO in the system. For this purpose, according to the ANSP's perspective, it is necessary to monitor the everyday work in order to identify potential deviations from the standard ICAO phraseologies and the level of standard aviation English of the ATCOs. More in detail, it is necessary to monitor if the full aircraft or vehicle call sign is really used (in everyday work) for all communications associated with the runway operations. Furthermore, it is necessary to verify if the communications associated with the operation of each runway are conducted on the same frequency as for take-off and landing of aircraft. Other relevant monitoring indicators can be developed, comparing the FRAM outcomes with (ICAO, 2007).

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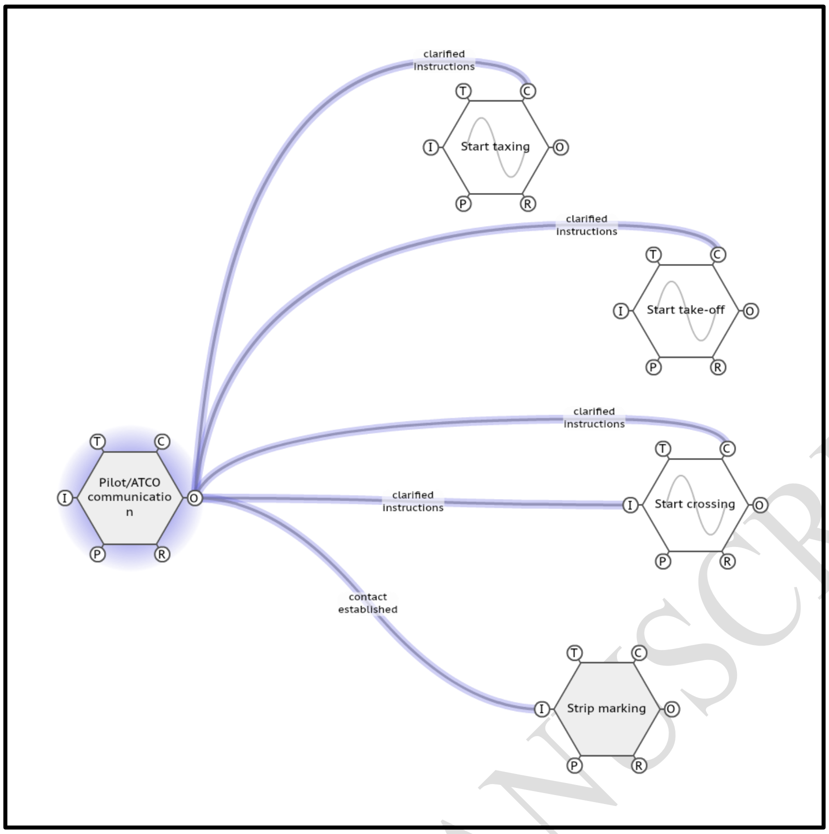

Figure 7. A critical path for RIN in the less critical scenario (Scenario 1).

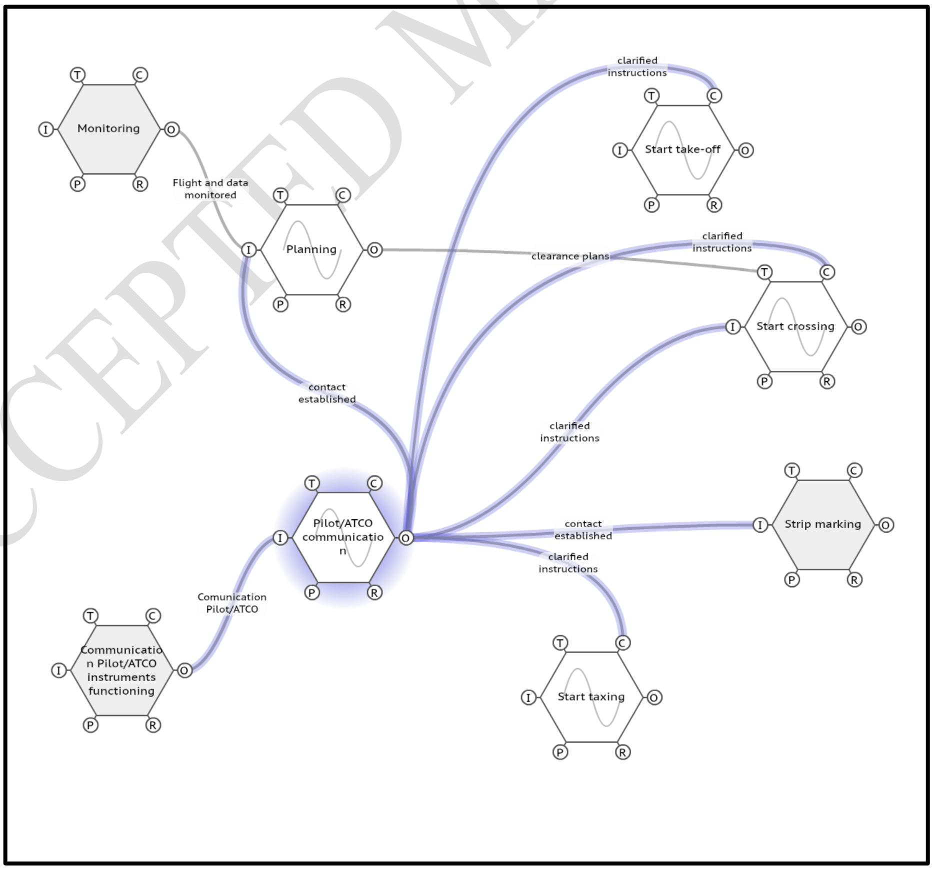

Figure 8. A critical path for RIN in the most critical scenario (Scenario 6). Note as the operating conditions make additional critical couplings emerge, if compared to Scenario 1 (see Figure 7).

5 Conclusions

FRAM facilitates a strong system analysis in order to have a clear description of the system functions, studying their interactions rather than the single probability of failure. The nonlinear nature of FRAM allows to identify static and transient links between human organization and technological functions.

The first outcome of the FRAM analysis shows a model of functions that describe how performance variability may occur in everyday operations and how this can be resonant through the system. This model identify potential sensitive areas in the system's functioning to take mitigating actions. Eliminating the hazard, if possible, or introducing barriers are the traditional ways to manage this variability.

The second outcome of the FRAM, i.e. identifying the critical couplings and paths, also allows another classification. Determining the critical paths allows identifying the conditions where the everyday work may get out of control, due to the high performance variability. The FRAM addresses the choice of monitoring indicators which will offer the opportunity to properly understand the real operating scenario. Rather than generic indicators, the FRAM allows defining relevant indicators for the specific process, enhancing the monitoring's potential effort. On the basis of these indicators, it would then be possible to evaluate damping strategy for the variability that may generate unexpected or unwanted situation.

This work defines a semi-quantitative framework which aims to enhance traditional safety assessment for the ATM system. This method apply traditional FRAM theory proposing a Monte Carlo framework to define quantitatively the resonant system functions. This becomes possible because the unintended interactions of the everyday variability is not completely stochastic. Considering the variability of each function aspect, the paper highlights which functions have larger variability, in accordance with the functional resonance principle. Rather than simple numerical results, the approach developed in this paper aims to support the safety investigation process. These results aim to individuate the couplings due to particular transient causes which may not leave any traces if analyzed with traditional safety assessment techniques. It aims to guide the choice of monitoring indicators to address then the choice of the most effective mitigating actions. For this purpose, it would be possible to adopt the Aerospace Performance Factor, as a derivation of the Analytic Hierarchy Process (AHP) to have a clear depiction of the system state. APF and AHP have been recently proved (Di Gravio et al., 2016, 2015b; Futron Corporation, 2010) useful in the ATM safety management. Further research can consider a more powerful scenarios' variability in order to better define real case situations. Even a more detailed analysis, based on the evidence of real data may help at validating the method. In addition, the promising results of this paper highlight the possibility to adapt this semi-quantitative approach of FRAM in different socio-technical systems, where a high complexity level requires an evolution of the traditional safety assessment methods.

Acknowledgements

The authors develop a VBA code to execute the semi-quantitative analysis conducted in this study and they interface it with the FRAM Model Visualizer (FMV), a software written and developed by Rees Hill, which the authors greatly acknowledge for his contribution to the development of FRAM.

The authors would like to thank professor Erik Hollnagel for his support and encouragement and to have drawn this path of research which in the next future will prove its effectiveness on complex systems as early results already show.

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