The Functional Resonance Analysis Method (FRAM) on Aviation: a Systematic Review

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The development of the Functional Resonance Analysis Method (FRAM) has been motivated by the perceived limitations of fundamentally deterministic and probabilistic approaches to understand complex systems' behaviour. Congruent with the principles of Resilience Engineering, over recent years the FRAM has been progressively developed in scientific terms, and increasingly adopted in industrial environments with reportedly successful results. This paper aims to summarize available documents published between 2017 and 2022 about FRAM in the Aviation domain through a Systematic Literature Review (SLR). Seventeen (17) articles were reviewed, disclosing characteristics of the FRAM research regarding the method's application as well as proposing potential future research directions.

Keywords: Aviation, FRAM, Systematic Review.

1. Introduction

Complex systems comprise different groups of humans, technologies, and organisations that may interact non-linearly with each other in many industrial domains (Tian & Caponecchia, 2020). The Functional Resonance Analysis Method or FRAM derived from a need to understand and describe how performance in these complex dynamic socio-technical systems unfolds and how the "mechanisms" behind everyday performance variability may be modelled (Patriarca et al., 2020).

FRAM is a method-sine-model, which focuses on the system functioning rather than the structure of its components (Tian & Caponecchia, 2020). Its purpose is to build a model of how things happen rather than to interpret what happens in the terms of a model.

The method was originally established to investigate accidents and incidents in complex socio-technical systems (i.e., FRAM - Functional Resonance Accident Model). It was subsequently expanded to a more general analysis method, focusing on the variabilities in the daily working procedure. Nowadays, FRAM is being used for retrospective analyses (i.e., analyses of accidents or other events), and for prospective ones (i.e., mainly analyses of current work domain or envisioned scenarios for risk management) (Patriarca et al., 2020).

FRAM is built over the following four principles. First, failures and successes are equivalent in the sense that they have the same origin. In other words, things go right and go wrong for the same reasons. Second, the everyday performance of socio-technical systems, including humans individually and collectively, is always adjusted to match the conditions. Third, many of the outcomes we notice – as well as many that we do not – must be described as emergent rather than resultant. Fourth, the relations and dependencies among the functions of a system must be described as they develop in a specific situation rather than as predetermined cause–effect links. This is done by using functional resonance (Hollnagel, 2012).

The modelling process consists of four steps. First, the complex sociotechnical system is deconstructed into "functions", that represent a task, or an activity, required to produce a certain outcome. Second, the variabilities of the functions are characterized. Third, specific instantiations of the model are examined to understand how the potential variability of each function can become resonant, leading to unexpected results. Fourth, performance variability is monitored and managed.

Due to the potential value of FRAM in system modelling and safety, this work aims to summarize available papers published between 2017 and 2022 about FRAM on Aviation through a Systematic Literature Review (SLR) in order to gain an understanding of how the method is being applied on this domain.

2. Methods

A SLR is a means of identifying, evaluating, and interpreting all available study relevant to a particular research question, or topic area, or phenomenon of interest. One of the most common reasons to perform a SLR is "To provide a framework/background to appropriately position new research activities". Kitchenham (2004) provide guidelines to accomplish a SLR, in which three main phases are considered: (1) Planning the review; (2) Conducting the review and (3) Reporting the review (Fig. 1).

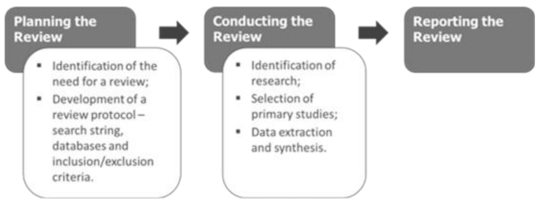

Fig. 1 - Phases of the SLR

2.1. *Planning the Review*

First, the need for a review must be identified to summarize all the existing information about a topic in a thorough and unbiased manner. The current SLR aims to identify relevant research regarding the use of FRAM on aviation. It intends to answer the following question: "Is FRAM being applied on aviation? How? For what?".

Secondly, a SLR protocol must be developed. The protocol defines, for instance, the sources and strings used to identify the primary studies as well as the inclusion/exclusion criteria applied to these studies' selection. The current review was performed over the *Portal de Periódicos da Coordenação de Aperfeiçoamento de Pessoal de Nível Superior* (CAPES), which is one of the largest virtual scientific collections and comprises bases like Scopus, Science Direct and Web of Science. The search strings were chosen as shown in Fig. 2.

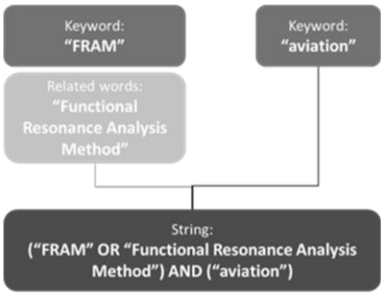

Fig. 2 - Search String for the Review

The study selection criteria determine principles for including in, or excluding, a research paper from the SLR. This review includes documents that apply FRAM in the aviation domain. It excludes documents that are not written in English; are not available; are duplicated; are not formatted as a paper; do not have any relation with the topic; and were written more than 5 years ago.

2.2 *Conducting the Review*

Once the protocol has been established, the review may begin. Initially, the search string was submitted to the selected collection, the *Portal de Periodicos da* CAPES. This step already excluded publications written in non-English languages and more than 5 years ago. The database returned 137 publications, being 135 articles. Some articles were removed because they were related to topics like Life Sciences & Biomedicine, Social Sciences, and Physical Sciences. The title and abstract of the remaining 73 documents were read, and 9 were selected for a complete read out (Table 1). Some of their references were also explored to complete the systematic review (Table 2), totalizing seventeen (17) papers. The selected papers consisted of a FRAM application on aviation domain, some systematic reviews, and comparisons with other methods.

2.3 *Reporting the Review*

A total of seventeen (17) papers were completely read out and their scope are detailed in this section. The last three years were fulfilled with Systematic Reviews. Patriarca et al (2020) is a systematic analysis that reviewed more than 1,700 documents to explore the FRAM in terms of its methodological aspects, application domains, and enhancements in qualitative and quantitative terms, as well as proposing potential future research directions.

Salehi et al. (2020) is a review paper of 52 peer-reviewed journal articles that have employed FRAM and were published between 2010 and 2020. They explored 9 aviation-related studies. Most of them aim to understand and analyse accidents, incidents, or events that happened in the past.

Tian & Caponeccia (2020) performed a systematic review of FRAM studies, with an emphasis on how it has been applied in aviation. They identified 108 existing FRAM studies from 2006 to 2019, being 26 related to aviation.

Hulme et al. (2019) examined peer-reviewed studies that have applied AcciMap, HFACS, the Causal Analysis of the Systems Theoretic Accident Model and Processes (STAMP-CAST), and FRAM to analyse and understand the cause of accidents across a diverse range of socio-technical systems contexts. They analysed 73 documents, being four (4) related with FRAM.

According to Patriarca et al. (2020) and Tian & Caponeccia (2020), aviation is the most investigated domain with the FRAM. There is a need in this domain for approaches that deal with tight and non-linear couplings among human, technical and organizational factors (Lalis et al., 2019).

Among the 11 aviation FRAM studies examined in this paper (excluding the systematic reviews and the comparison with other methods papers), 8 (73%) used FRAM in a prospective way to assess risks, while the remaining 3 (27%) studies are a retrospective analysis. Slim et al (2018) and Patriarca et al. (2018) are examples of accidents analysed by FRAM in a retrospective way. The former examined the SAS flight 751 crash at Gottröra in 1991, that is related with clear ice on the wings prior to take-off. The latter applied the method to a runway incursion that happened in February 1991 at LAX airport, involving SkyWest Flight 5569 and USAir Flight 1493. The papers were related to Ground Handling and Air Traffic Control (ATC), respectively.

Studic et al. (2017) also performed a retrospective assessment in the Ground Handling domain by applying the Total Apron Safety Management (TASM) Framework to a low-severity occurrence. TASM is a FRAM model that was developed using Grounded Theory, the Template Analysis and Goals-Means Task Analysis (GMTA) for data sampling, collection, analysis, and validation.

The prospective analyses are mainly devoted to issues related to Air Traffic Control, like Ferreira & Cañas (2019), Karikawa et al. (2019), and Rutkowska & Krzyżanowski (2018). Ferreira & Cañas (2019) presents a FRAM-based analysis of the potential impacts of foreseeable automation over air traffic controller performance and behaviour. Karikawa et al. (2019) modelled the resilience of air traffic controllers in the control tower. Rutkowska & Krzyżanowski (2018) applied the FRAM' Step 1 for the aircraft' transfer of control between ATC units.

Adriaensen et al. (2019) addresses flight operations prospectively while Moškon et al. (2019) demonstrated their method on five (5) case studies, including a flight operation and an ATC one.

Most of the papers propose some enhancement on the traditional FRAM, indicating that the method is still evolving. The value of the Safety-II perspective in providing detailed recommendations for improving system safety is recognized, but FRAM is described as time consuming and complex to use and to interpret the results (Farooqi et al., 2022; Tian & Caponeccia, 2020; Hulme et al., 2019). In aviation, studies such as Lališ et al. (2019), Moškon et al. (2019) and Adriaensen et al. (2019) aim to facilitate FRAM model comprehension or even enable the automatization of the analysis.

Lališ et al. (2019) proposed the representation of a function by means of the Unified Foundational Ontology (UFO) in order to achieve improved and computer readable description of a FRAM' function concept, that would support future tools and software based on the FRAM itself. Their case study was based on Patriarca et al. (2017) one. Moškon et al. (2019) proposes a method to enhance FRAM through accurate declarations of inter-functional couplings.

Adriaensen et al. (2019) aim to develop a FRAM model to understand the information flow propagation in a cockpit environment under normal conditions, following a Joint Cognitive Systems (JCS) perspective. JCS would allow analysing how task-relevant information moves through the cockpit system by translating the representation of information in one medium into another.Additional point of attention was described as the absence of a quantitative analysis to estimate the risk. Salehi et al. (2020) cited the development of (semi-)automatic data collection approaches, including function identification and aspect specification, as well as method(s) for quantifying variability as a future research direction of FRAM. In aviation, the studies from the last five (5) years are still dominated by qualitative methodologies, with 7 papers (63%).

Nonetheless, Adriaensen et al. (2019) additionally used a semi-quantitative method to identify critical functional couplings through the number of downstream dependencies for each function.

Patriarca et al. (2018) proposes the Resilience Analysis Matrix (RAM) to enhance the strength of FRAM-based accident analyses by reducing the complexity of FRAM' representation. The RAM offers a two-dimensional representation which highlights systematically connections among couplings.

Yang et al. (2017) proposes a method based on FRAM by using formal verification as a supporting tool to efficiently check the functional resonance after identifying the couplings of functional variability. They used Simple Promela Interpreter (SPIN) to demonstrate the functional resonance in system and applied the proposed method to a developing Air Traffic Management (ATM) system where a Minimum Safe Altitude Warning (MSAW) subsystem is being introduced.

Patriarca et al. (2017) proposed a method to quantify and aggregate functions' variabilities in relation to the ATM system based on Monte Carlo simulation.

The remaining documents only compared FRAM with other methodologies. Farooqi et al. (2022) work focuses on understanding the choice and the use of different error and accident analysis methods by safety practitioners due to an existent "research-practice gap". Stogsdill & Ulfvengren (2017) proposes a method to evaluate several models and methods for safety and risk analysis feasibility to represent complex systems, like the ATC. FRAM was one of the better scored methods due to its capability to evaluate the level of coupling and non-linearities among system elements.

In summary, the purpose of the documents analysed in this paper is shown in Fig. 3. Note that the traditional FRAM is also qualitative.

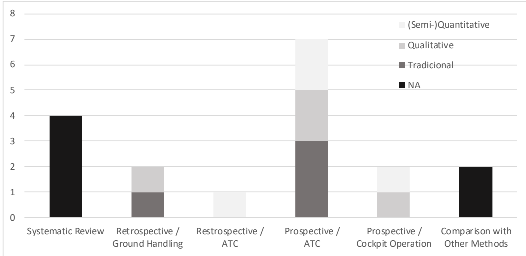

Fig. 3 – Documents Purpose

4. Discussion

The current SLR intends to answer the following questions: "Is FRAM being applied on aviation? How? For what?". Aviation is the most investigated domain with the FRAM, comprising circa of 25% of the documents (Patriarca et al., 2020; Tian & Caponeccia, 2020). It is being used for retrospective as well as prospective analyses in topics related to Air Traffic Control (ATC), Flight Operation and Ground Handling.

The "openness" of FRAM provides ample opportunities for its enhancement. FRAM was originally developed for retrospective analyses and expanded to contemplate prospective ones. In aviation, the latter was explored more often in the last five years due to a crescent need to understand the socio-technical behaviour of this highly complex work environment and to manage risks in an even more proactive way.

Due to the implementation of the Safety Management System (SMS) in most organisations of the current domain, sophisticated processes for data collection such as safety reporting systems and flight data monitoring are already available. The "absence of a quantitative analysis" point of attention regarding FRAM may be easily overwhelmed. For instance, FRAM focus on the everyday performance may be explored through the analysis of flight data in cockpit operations.

Flight data is the information coming from aircraft sensors, onboard computers and other instruments that are recorded into a crash-survivable Flight Data Recorder (FDR) and occasionally also into easily accessible Quick Access Recorder (QAR). They are already used on Flight Data Monitoring (FDM) programs, that are designed to enhance safety by identifying airlines' operational safety risks. FDM is based on the routine analysis of flight data during revenue flights (Delhom, 2014).

Reiser et al. (2022) proposes a customized FRAM for operational risk assessment related with an aircraft landing procedure - the touchdown. This paper uses FDM techniques to characterize the functions' variabilities, and a Monte Carlo basis to define quantitatively the system resonance. Flight data is the most precise and efficient way to collect unbiased data in the real world, at least regarding flight operations.

The control of single variability cannot fully eliminate hazards, justifying the existence of emergent hazards arising from variabilities' aggregation. To mitigate the emergent hazards, simultaneous control of multiple variability should be taken. To understand this dynamic is not a trivial task, even when evaluating qualitatively a FRAM model, that increases exponentially with the complexity of the system under analysis. FRAM is a method currently under development and evolving to a quantitative approach for prospective analyses.

Table 1 - Selected Papers

Author(s)	**Year**	**Title**	**Domain**	**Analysis Type**	**Research Type**	**Remarks**
Farooqi et al.	2022	Using expert perspectives to explore factors affecting choice of methods in safety analysis	General	NA	Comparison with Other Methods	
Salehi et al.	2020	Modeling complex socio-technical systems using the FRAM: A literature review	General	NA	Systematic Review	
Tian & Caponecchia	2020	Using the Functional Resonance Analysis Method (FRAM) in Aviation Safety: A Systematic Review	Aviation	NA	Systematic Review	
Hulme et al.	2019	What do applications of systems thinking accident analysis methods tell us about accident causation? A systematic review of applications between 1990 and 2018	General	NA	Systematic Review	Includes other methods, such as Accimap, HFACS[1] and STAMP[2]
Lališ et al.	2019	Functional modeling in safety by means of foundational ontologies	Air Traffic Control	Prospective	Qualitative Method Proposal	Enhancement of Step 1 by Using UFO[3]
Rutkowska & Krzyżanowski	2018	FRAM modelling of the transfer of control over aircraft	Air Traffic Control	Prospective	Case Study	
Patriarca et al.	2017	A Monte Carlo evolution of the Functional Resonance Analysis Method (FRAM) to assess performance variability in complex systems	Air Traffic Control	Prospective	Semi-Quantitative Method Proposal	Enhancement of Steps 2 and 3 Using Monte Carlo Simulation
Studic et al.	2017	A systemic modelling of ground handling services using the functional resonance analysis method	Ground Handling	Retrospective	Case Study	Use of the TASM[4] framework
Stogsdill & Ulfvengren	2017	Mapping Risk Models/Methods onto a Complexity Spectrum	Air Traffic Control	NA	Comparison with Other Methods	

1 Human Factors Analysis and Classification System

2 Systems Theoretic Accident Model and Processes

3 Unified Foundational Ontology

4 Total Apron Safety Management

Table 2 - Cited Papers

Author(s)	**Year**	**Title**	**Domain**	**Analysis Type**	**Research Type**	**Remarks**	**Cited by**
Patriarca et al.	2020	Framing the FRAM: A literature review on the Functional Resonance Analysis Method	General	NA	Systematic Review		Farooqi et al (2022)
Ferreira & Cañas	2019	Assessing operational impacts of automation using functional resonance analysis method	Air Traffic Control	Prospective	Case Study		Salehi et al. (2020) and Tian & Caponeccia (2020)
Adriaensen et al.	2019	A socio-technical analysis of functional properties in a joint cognitive system: a case study in an aircraft cockpit	Flight Operation	Prospective	Semi-quantitative Method Proposal	Enhancement of Step 3 via JCS[1] perspective	Salehi et al. (2020) and Tian & Caponeccia (2020)
Karikawa et al.	2019	Resilience of Air Traffic Controllers in control tower	Air Traffic Control	Prospective	Case Study		Patriarca et al. (2020)
Moškon et al.	2019	Towards the Declaration of Inter-Functional Protocol for FRAM	Flight Operation & Air Traffic Control	Prospective	Qualitative Method Proposal	Enhancement of Step 3 via an Inter-Functional Protocol	Tian & Caponeccia (2020)
Patriarca et al.	2018	FRAM for Systemic Accident Analysis: A Matrix Representation of Functional Resonance	Air Traffic Control	Retrospective	Semi-quantitative Method Proposal	Enhancement of Step 3 via RAM[2]	Tian & Caponeccia (2020)
Slim et al.	2018	FRAM: A Complex System's Approach for the Evaluation of Aircraft On-ground Deicing Operations	Ground Handling	Retrospective	Case Study		Patriarca et al. (2020)
Yang et al.	2017	Safety is an emergent property: Illustrating functional resonance in Air Traffic Management with formal verification	Air Traffic Control	Prospective	Quantitative Method Proposal	Enhancement of Step 3 using Formal Verification	Salehi et al. (2020) and Tian & Caponeccia (2020)

1 Joint Cognitive Systems

2 Resilience Analysis Matrix

5. Conclusions

FRAM is appreciated as a useful tool to build an understanding of non-linear dependencies, performance conditions, variability, and their resonance across functions. The concept of functional resonance is innovative and has been used to explain a number of safety issues. Therefore, researchers from different areas are expanding the application of FRAM in a wide range of contexts, including aviation.

The current Systematic Literature Review (SLR) examined seventeen (17) articles related to FRAM on Aviation. It was performed to provide a background to appropriately position a new research activity, that comprises the use of a customized and quantitative FRAM to model runways overruns with the addendum of Flight Data Monitoring (FDM) techniques.

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