Safety Science 129 (2020) 104827

Contents lists available at ScienceDirect

Safety Science

journal homepage: www.elsevier.com/locate/safety

Framing the FRAM: A literature review on the functional resonance analysis method

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ARTICLE INFO

Keywords:
Systematic review
Complex systems
Socio-technical systems
Resilience engineering
Safety

ABSTRACT

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. Nevertheless, a wide literature review focused on the method is currently lacking. On these premises, this paper aims to summarise all available published research in English about FRAM. More than 1700 documents from multiple scientific repositories were reviewed through a protocol based on the PRISMA review technique. The paper aims to uncover a number of characteristics of the FRAM research, both in terms of the method's application and of the authors contributing to its development. The systematic analysis explores the method in terms of its methodological aspects, application domains, and enhancements in qualitative and quantitative terms, as well as proposing potential future research directions.

1. Introduction

The scientific background for the FRAM has briefly been described in the Prologue to the FRAM book (Hollnagel, 2012). The most important influence is the realisation that there is a need to understand and describe how performance in complex dynamic socio-technical systems unfolds and how the "mechanisms" behind everyday performance variability may be modelled. In an early reflection on the nature of "human error", Hollnagel wrote that "*We must not forget that in a theory of action, the very same mechanisms must also account for the correct performance which is the rule rather than the exception*" (Hollnagel, 1983). The idea that performance variability and emergence could be interpreted as beneficial for understanding successful action and performance has therefore been around for some time. However, methods that facilitate analysis and understanding of everyday performance (variability) according to this perspective have lagged behind. The more deliberate development of the FRAM started around 2000 and resulted in the first description of the method in 2004. At that time, the acronym meant "Functional Resonance Accident Model". This was because the start had been in R&D related to safety, and safety was at that time closely related to accidents – what is now often called Safety-I. The same was the case for Resilience Engineering in its initial version. Intense discussions during the first FRAMily meetings, however, made it clear that the FRAM was a method rather than a model, and that it furthermore was a method that could be used for complex socio-technical systems in general rather than just for accident analysis. Fortunately, the acronym could still be kept to mean "Functional Resonance Analysis Method". More generally, as a method the FRAM is used to produce a representation – called a model – of how work is done.

For reasons that no one really understands, the FRAM became known rather quickly after the first publication (Hollnagel, 2004).

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https://doi.org/10.1016/j.ssci.2020.104827
Received 16 January 2020; Received in revised form 3 April 2020; Accepted 8 May 2020
Available online 22 May 2020

Fig. 1. Location of FRAMily meetings over years (2007–2019).

Shortly after Hollnagel began a new position at École des Mines in Sophia Antipolis in the south of France, and this provided an opportunity – and a congenial environment – to organise very informal meetings where the method and its further development were discussed. After a couple of meetings, a bright PhD student came up with a name for that: the FRAMily. The name stuck, the number of attendants started to grow. Informal meetings gradually became more structured workshops that are continuing to this day. After 15 years from its original proposition, 13 FRAMily annual international meetings (see Fig. 1), numerous workshops, courses, and research projects make clear that a wide range of applied FRAM studies in a variety of domains and for various purposes have been performed, applying, using, or extending on the FRAM.

FRAM related papers have so far provided fragmented reviews adopting pragmatic inclusion criteria relevant for the specific scope of the paper (i.e. a specific domain, a specific quantification approach, specific sets of accident analyses, etc.). Furthermore, the only review currently available on the FRAM presents only a very small sample of the available literature, i.e. 22 documents (Pardo-Ferreira et al., 2019). Thus, no comprehensive collection and description of the state-of-the-art in application of the FRAM is available to practitioners and academics who wish to be aware of its practical applications and developments since its inception.

On these premises, this paper aims to fill this gap through a review of all indexed English literature on the FRAM. The purpose is to gain an understanding of existing research on the FRAM, focusing on the empirical evidence published on its application and further development. A knowledge summary is provided to emphasize the FRAM added value and trade-offs for its application to model non-trivial socio-technical systems. Adopting a systematic perspective, the review process used explicit criteria to identify, select, and critically analyse relevant documents. A *meta*-narrative review is presented to summarise the results of the included studies in terms of qualitative description and relevant statistical analyses.

The remainder of the paper is organised as follows. Section 2 details the sources used for the analysis and the systematic approach followed to finalise the review dataset. Section 3 presents descriptive analyses on the final dataset, while Section 4 details all the interpretative results derived from the search. Section 5 summarises the outcomes of the research, as well as it discusses the historical development of the FRAM in light of potential future research paths. Lastly, the conclusions provide overall reflections on the status of the method itself.

2. Materials and methods

The systematic approach followed in this research relies on PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-analyses) (Moher et al., 2009). Nevertheless, the approach has been revised

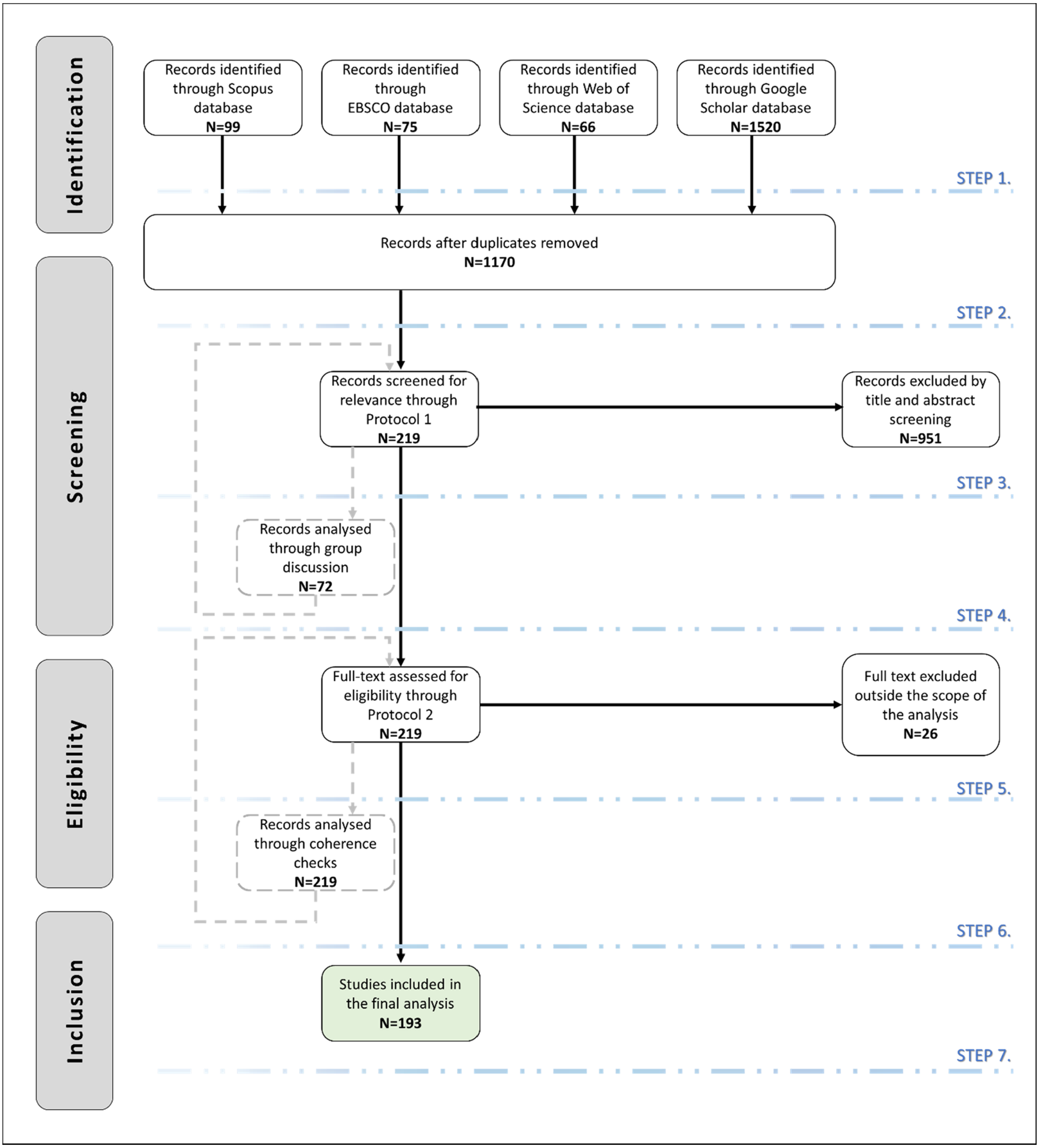


Fig. 2. Literature search strategy.

according to the dataset and contributions, through dedicated protocols and data quality checks.

2.1. Researchers' background

The review has been conducted by six researchers with different backgrounds (three industrial engineers, a cognitive systems engineer, a cognitive scientist, and a human factors engineer), who are all involved in risk and safety research and work activities. All researchers have a broad experience on Resilience Engineering and the FRAM, with four of the researchers' PhD theses making substantial use of the method. The researchers have an average working and researching experience with the FRAM of more than 8 years, with two of them being part of the FRAM research community since the very first meetings.

2.2. Steps of the approach

Starting from PRISMA (Moher et al., 2009), our methodological approach consisted of 7 phases. It was implemented through several Excel datasheets following customised protocols, as sketched in Fig. 2.

STEP 1. Selecting databases, and setting the search query

The first step of the review defined the scope of the search query. A wide query was deliberately chosen in order to include all potential contributions linked to the FRAM. The final search query included every paper making use of “functional resonance analysis method” or “functional resonance accident model” in title or abstract or keywords for contributions indexed up to August 2019. Firstly, the query referred to the Scopus database as a main source, since it is the biggest repository of peer-reviewed literature with over 5000 publishers and over 71 million records fairly balanced among technical and social aspects of science (Elsevier, 2018). However, considering the potential amount of literature on the FRAM not indexed in Scopus (some conferences, theses, white papers, etc.), it has been considered necessary to enlarge the query to other databases, i.e. EBSCOhost, Web of Science, Google Scholar. All datasets except Google Scholar allowed the usage of a structured query, (e.g.) documents filtered for title and abstract content: TITLE-ABS (“functional resonance analysis method“ OR ”Functional resonance accident model”). Google Scholar required the development of a python script to bypass the restriction on massive data extraction. We nevertheless decided to include Google Scholar in the review, since it has been recognised as the largest and most frequently used (although least understood and validated) of the academic search engines and bibliographic databases (ASEBDs) (Gusenbauer, 2019).

STEP 2. Refinement of dataset

The query returned a total number of 1760 items matching the search criteria. As a first step, a preliminary data refinement on the title especially for non-systematic data extraction files, such as the one from Google Scholar, was conducted to eliminate duplicates. As a result, 590 duplicates were identified and deleted. 1170 items remained in the dataset for the review.

STEP 3. Screening through Protocol 1

The output of this step was to identify relevant items to be included in the review. Each researcher was responsible for 195 documents out of the 1170. Each abstract was screened according to the following criteria:

- Surely NO
  - o IF NOT in English, or
  - o IF in English AND (Document Type B) AND (theme out of scope).
- Surely YES
  - o IF in English AND (Document Type A) AND (theme in scope)
- Maybe
  - o IF in English AND (Document Type B) AND (theme possibly in scope)

With respect to Document Type, the protocol foresees two families:

- Document Type A
  - o Journal Article
  - o Conference Proceedings
  - o Book
  - o Book Chapter
  - o Paper-based PhD Thesis
  - o Monography PhD Thesis
  - o Technical/Institutional official report
- Document Type B
  - o Editorial
  - o Book Review
  - o Undergraduate Thesis
  - o Graduate Thesis
  - o Poster
  - o Presentation
  - o Abstract
  - o Webpage
  - o Unpublished report
  - o White Paper
  - o Other

Following the scope of the paper, many documents were excluded because they were just mentioning the FRAM as a potential analysis method, with no application or detail of the FRAM itself.

Protocol 1 also aimed to refine the *meta*-data and information about the included publications, i.e. define the aim of the paper as an accident analysis (i.e. a retrospective analysis of an event); risk assessment (a prospective analysis of an envisioned system); or system modelling (any other generic approach for modelling a socio-technical process). In addition, Protocol 1 led to the identification of whether the perspective used in the study was a qualitative, or a quantitative/semi-quantitative one. An indication of the authors’ geographical area was included (one for each author of a paper, and thus potentially many for each paper). The results showed 72 documents requiring further investigation (“Maybe” in Protocol 1), which ended up in 219 documents to be analysed using Protocol 2, and 879 to be disregarded for the following steps.

STEP 4. Analysis through group discussion

Once each researcher individually applied Protocol 1 to all of their assigned documents, the 72 documents requiring further investigation were filtered through a group discussion involving three researchers. Preliminarily, the three researchers individually reviewed full-text and abstract of such papers to propose a final decision on their inclusion (24 papers each), re-reviewing documents that were not previously assigned to them at Step 3. The results of individual reviews were then discussed jointly to take a final decision.

STEP 5. Eligibility assessment through Protocol 2

Protocol 2 represents the analysis of the included publications. To decrease the effects of potential biases in the selection of the included review items identified through Protocol 1, a different set of publications was assigned to each researcher. In particular, Protocol 2 included the analysis of the FRAM building steps adopted in the paper (if any), strategy for data collection, size of the model (in terms of number of functions). Further aspects were connected to potential changes declared by the authors to Hollnagel’s methodological framework, providing their details (if any), and to the adoption of the FRAM as part of a bigger methodology. Another field was dedicated to outline models or methods used in the selected papers and compared to the FRAM outcomes. The role of industry agents, as informants, or as authors were requested to be acknowledged, as well as software used in the analysis. For theses, faculty and major subject were recorded. Full details on Protocol 2 are attached in the Appendix.

STEP 6. Coherence check

Following the results of Protocol 2, two researchers re-assessed the coherence of the provided assignments. These coherence checks were intended to increase the quality and reliability of the analysis, following some simple rules to highlight cases where revision was necessary, (e.g.):

- IF any Protocol 1 or Protocol 2 field is “empty”
- IF ≪Declared change of the methodology≫ AND ≪“No method mentioned”≫
- IF ≪Semi-Quantitative/Quantitative perspective≫ AND ≪No declared change of the methodology≫

STEP 7. Analysis of papers included in the final dataset

The last step consisted of analysing the full text of each paper in the final dataset, as well as providing some bibliometric analysis on respective authors (see Section 3.3).

A logic for the analysis and presentation of results was defined, leading to individual researchers being responsible for a subset of documents aligned to a topic or question(s) in the dataset. Considering the authors' background, the analysis of full text followed a deductive perspective, with an unconstrained categorization: iteratively adding different categories was allowed within the bounds of the protocols following the principles of inductive content analysis (Elo and Kyngäs, 2008). Based on the results of this categorization, documents have been presented following a structured logic to facilitate the narrative dimension of the document (see Section 4).

In practical terms, the adopted logic led to identify two usages of the method, namely:

- *FRAM for retrospective analyses*, i.e. analyses of accidents or other events;
- *FRAM for prospective analyses*, i.e. mainly analyses of current work domain or envisioned scenarios for risk management, or other types of performance management.

Additionally, some *meta*-dimensions have been identified following the logic presented in Step 7 (see Section 2.2) (Elo and Kyngäs, 2008):

- *Change of the method*, i.e. documents describing any change of the method in terms of either qualitative aspects or quantitative ones;
- *FRAM as part of a bigger methodology*, i.e. documents using the whole method as an intermediate step for larger-scale approaches for larger-scale modelling;
- *Comparison with other methods or models*, i.e. documents mainly focused in presenting a FRAM application and comparing its outcome with another approach (e.g. Failure Mode and Effect Analysis, Fault Tree Analysis, Accimap, etc.).

Note that the category "Change of the method" differs to the "FRAM as part of a bigger methodology" since the former includes documents modifying one specific building step of the method, while the latter had a larger dimension in which FRAM is applied together with other activities or methods as part of a larger approach.

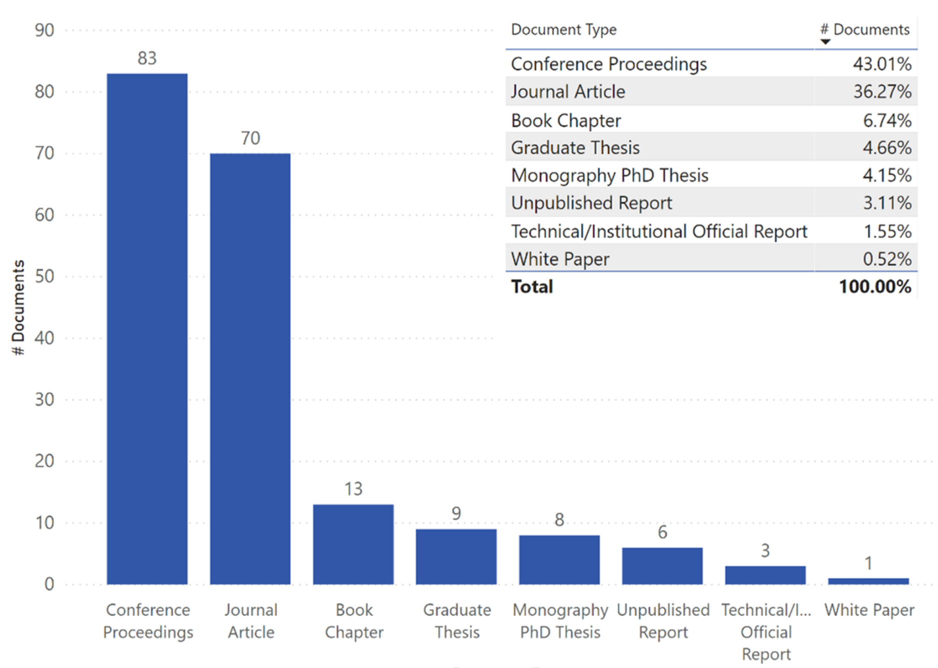
3. Descriptive results

The descriptive analysis identifies both quantitative characteristics of the research sector and its evolution over time. In this section, four principal areas of investigation are described and commented, i.e. publishing placement, domains of application, authors, statistics on the models. A Microsoft Power BI Business Intelligence dashboard has been developed for the analysis. Its main outcomes are listed in Sections 3.1 - 3.4.

3.1. Publishing placement

One of the first analyses considers the document types in the dataset in order to understand the past and present publication channel of documents about the FRAM. Even if Fig. 3 shows the predominant role of conference proceedings, it highlights the increasing presence of publications in journals, with a balanced proportion between conference proceedings and journal articles over recent years. Note that in Fig. 4, the category Other includes all document types shown in Fig. 3, which are neither Conference Proceedings, nor Journal Articles.

Subsequently, the analysis showed the most relevant journals in the dataset: 70 documents appear in 38 journals, but only 8 journals present more than one document, i.e. Reliability Engineering & System Safety (13 documents), Safety Science (8 documents), Cognition, Technology & Work (7 documents), Applied Ergonomics, Journal of Loss Prevention in the process Industries (3 documents each), American Journal of Industrial and Business Management, Ergonomics, Journal of the Ergonomics Society of Korea (2 documents each). On the other hand, 83 documents have been published in conference proceedings, linked to 54 congresses, among them: REA – the Resilience Engineering Association's Symposium (11 documents), ESREL - European Safety and Reliability Conference (6 documents), IFAC – International Federation on Automatic Control (5 documents).



Document Type	# Documents
Conference Proceedings	43.01%
Journal Article	36.27%
Book Chapter	6.74%
Graduate Thesis	4.66%
Monography PhD Thesis	4.15%
Unpublished Report	3.11%
Technical/Institutional Official Report	1.55%
White Paper	0.52%
Total	**100.00%**

Fig. 3. Document types in the dataset.

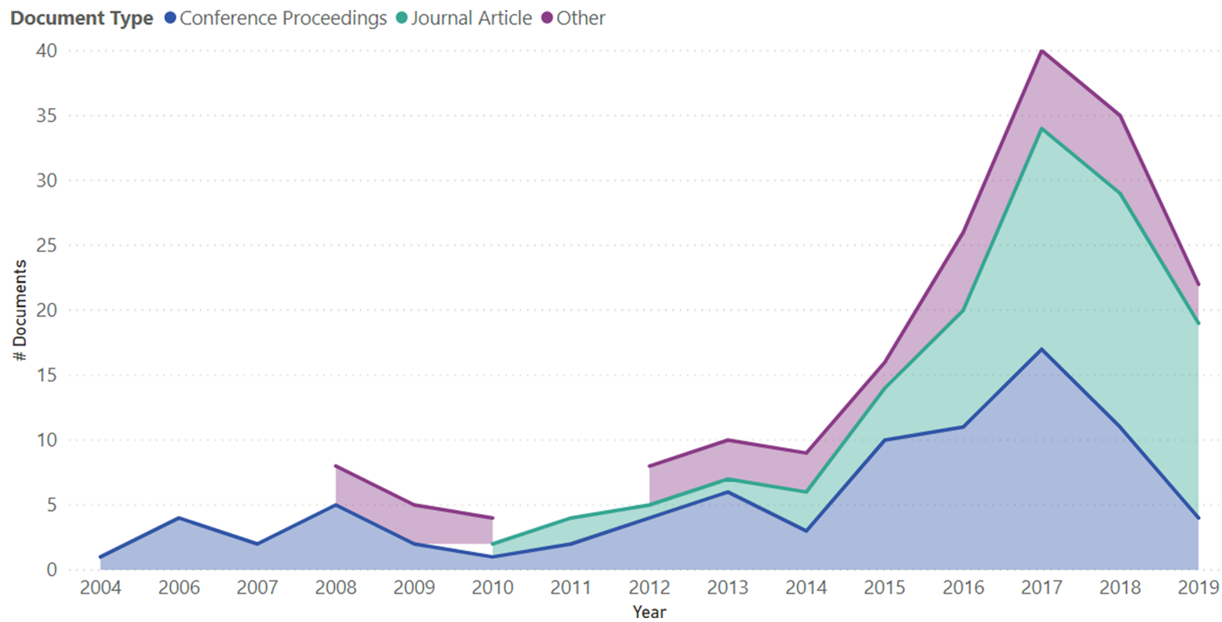
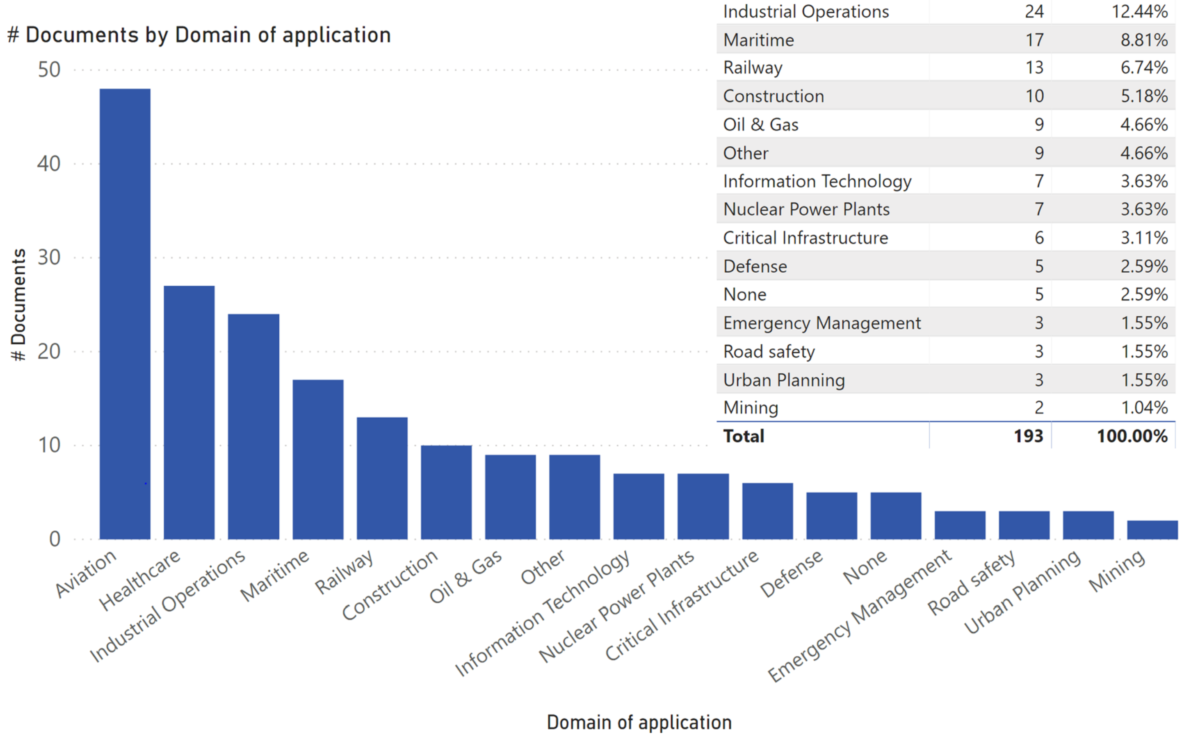


Fig. 4. Evolution of document types over years.

3.2. Domain of application

This analysis shows that Aviation is by far the most investigated domain with the FRAM (see Fig. 5). The strong initial focus by early FRAM scholars was on aviation safety, and it still is of primary interest (see Fig. 6). Healthcare settings also present a significant interest in the FRAM, as well as industrial processes. Other Transportation domains investigated through the FRAM are maritime and railway. In Fig. 5, domains accounting for just 1 document each have been included under the label "Other", i.e. "Product Design", "Security", "Finance and



Domain of application	# Documents	% Documents
Aviation	48	24.87%
Healthcare	27	13.99%
Industrial Operations	24	12.44%
Maritime	17	8.81%
Railway	13	6.74%
Construction	10	5.18%
Oil & Gas	9	4.66%
Other	9	4.66%
Information Technology	7	3.63%
Nuclear Power Plants	7	3.63%
Critical Infrastructure	6	3.11%
Defense	5	2.59%
None	5	2.59%
Emergency Management	3	1.55%
Road safety	3	1.55%
Urban Planning	3	1.55%
Mining	2	1.04%
Total	**193**	**100.00%**

Fig. 5. Domains of application in the dataset, by number of documents.

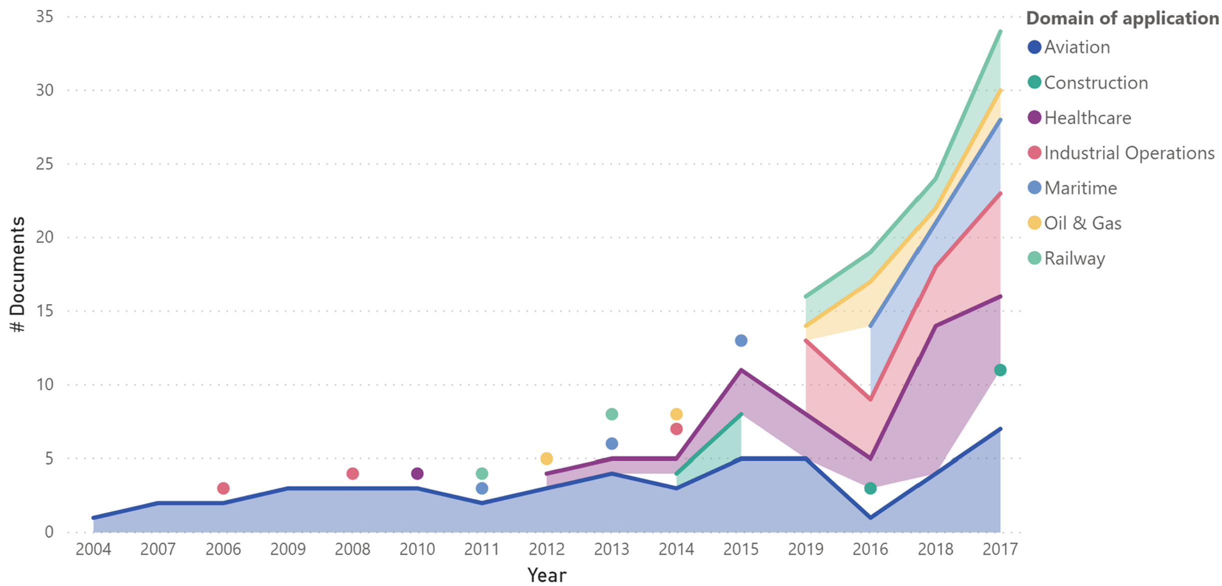


Fig. 6. Evolution of the top domains of application.

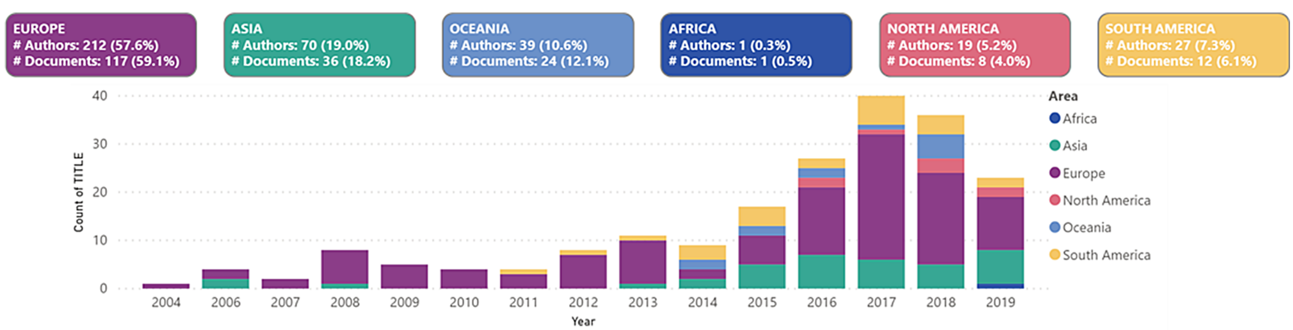


Fig. 7. Worldwide distribution, and evolution of documents for geographical areas.

Table 1
Top authors and placement of the documents for more than 5 documents/author.

Author	Conference Proceedings	Journal Article	Book Chapter	Monography PhD Thesis	White Paper	Tech/Inst Official Report	Unpublished Report	Total
E Hollnagel	11	9	1		1	1	1	**24**
R Woltjer	10	1	2				1	**14**
R Patriarca	5	7						**12**
PVR de Carvalho	3	6						**9**
TA Saurin	4	2	3					**9**
F Costantino	4	4						**8**
G Di Gravio	4	4						**8**
J Tian	4	4						**8**
M Ragosta	5			1				**6**
A Bahoo Toroody	1	4						**5**
L Macchi	3			1		1		**5**
MA Sujan	5							**5**
S Nadeau	3	2						**5**

Economics", "Space Missions", "Education", "Decision Making", "Neuroscience", "Project Management", and "Hunting".

3.3. Authors

Three analyses have been performed to explore different authors' interactions: authors' institutions' geographical origins, top authors by number of documents, and co-authorship analysis. The first analysis consists of a graphical distribution of authors' institutions in the dataset. Fig. 7 shows the most frequent occurrence of authors from Europe, followed by Asian scholars, in particular from China. Europe and China stand for about 70% of the overall number of documents. The contributions from South America (mainly Brazil) and Oceania are lower, as well as those by North American researchers. One contribution (single author) comes from Africa.

The analysis of the most prolific authors shows that more than 40% of the total number of documents (80 of 193) is due to 13 authors out of 355 authors in the dataset. The production of the top 13 authors is mostly balanced between journals and conferences (see Table 1).

A co-authorship analysis leads to the network presented in Fig. 8: the 355 authors in the dataset are symbolised as network nodes, and connection links come from the co-authorship of one or more

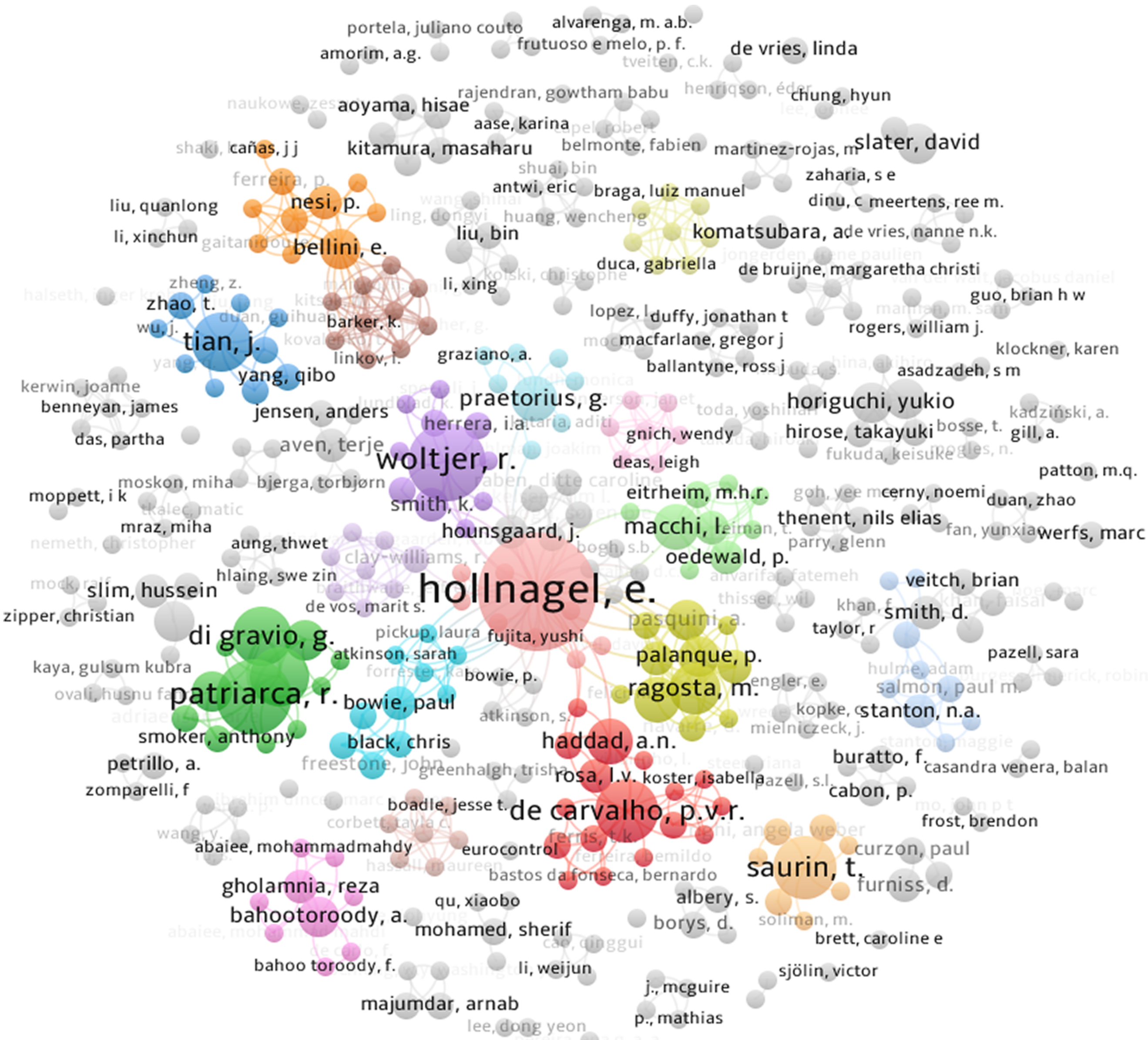


Fig. 8. Co-authorship network, with groups of researchers frequently co-authoring documents coloured.

documents in the dataset, i.e. if two authors wrote a joint paper, they will be linked. An intertwined web of links is expected around Hollnagel, the FRAM's originator and most active author. While the biggest 20 clusters have been coloured in the map, some major sub-networks of co-authors can be identified around Woltjer, Patriarca, Tian, De Carvalho, and Saurin. Additionally, it is possible to add a temporal dimension to this analysis, including the average publication year of contributions authored by each scholar. For graphical reasons, this analysis has been limited to the authors who published at least 2 contributions (see Fig. 9). Besides the initial applications of the method by Hollnagel, Woltjer, and then Macchi, Pasquini, Sujan, Rigaud, Ragosta, the FRAM has been increasingly used by other scholars directly collaborating with Hollnagel (e.g., Praetorius, and Hounsgaard) or scholars mainly independent such as the Brazilians De Carvalho and Saurin, as well as the Italians Patriarca et al. and the Chinese Tian et al. New authors are recently becoming active within this community, (e.g.) scholars from Canada (Hussein, and Nadeau), Japan (Karikawa, Aoyama, Ohashi, Takahashi, and Kitamura), Denmark (Mikkelsen et al.), and the UK (Bowie et al.).

3.4. FRAM models

The documents in the dataset mainly present method applications, with 11% of documents being purely theoretical. This percentage includes research that does not present complete FRAM applications, but rather methodological advancements or conceptual comments on the method. This fact is coherent with the setting of the keywords and research protocols (see Section 2), that narrowed the focus of the dataset to any FRAM applied studies. Referring to the standard application of the method and to its 4 steps (labelled here as 1. Description of system functions, 2. Identification of potential variability, 3. Definition of functional resonance, 4. Monitoring of resonance and mitigation), Fig. 10 reports most of the documents presenting full application of the FRAM (all 4 steps), with a relevant percentage of studies ending with step 3.

The aim of the FRAM models in the dataset can be classified as "retrospective" or "prospective": retrospective documents present FRAM applications to get insights and lessons learned from previous events or accidents; prospective documents include FRAM applications

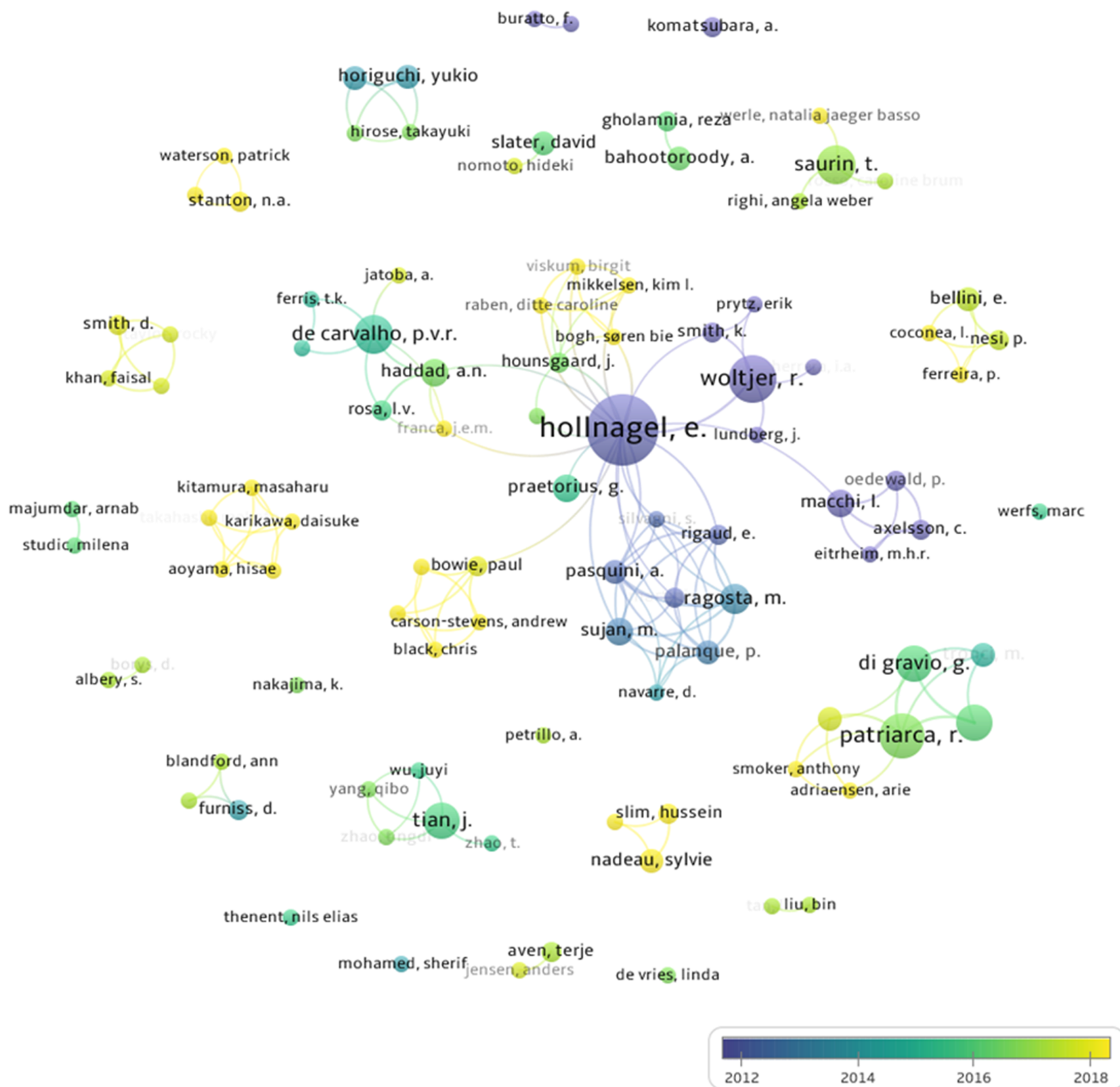


Fig. 9. Year distribution of co-authorship network (at least 2 publication per author).

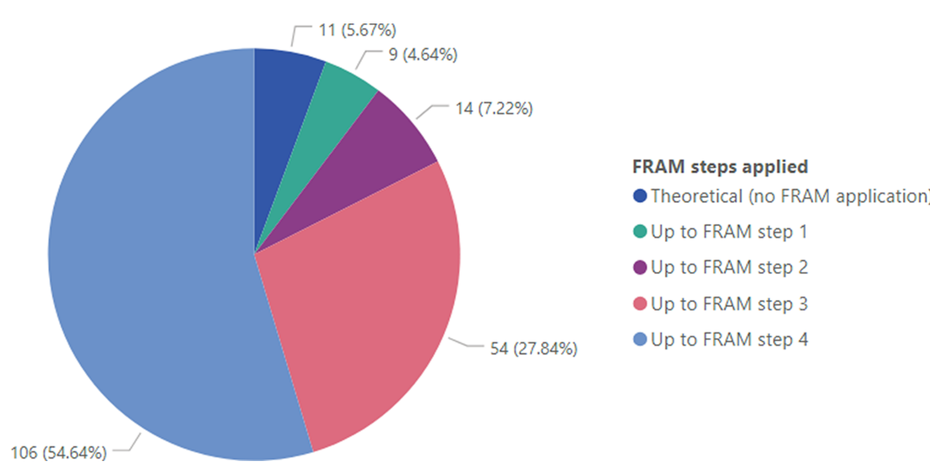


Fig. 10. FRAM steps application by # Documents in the dataset.

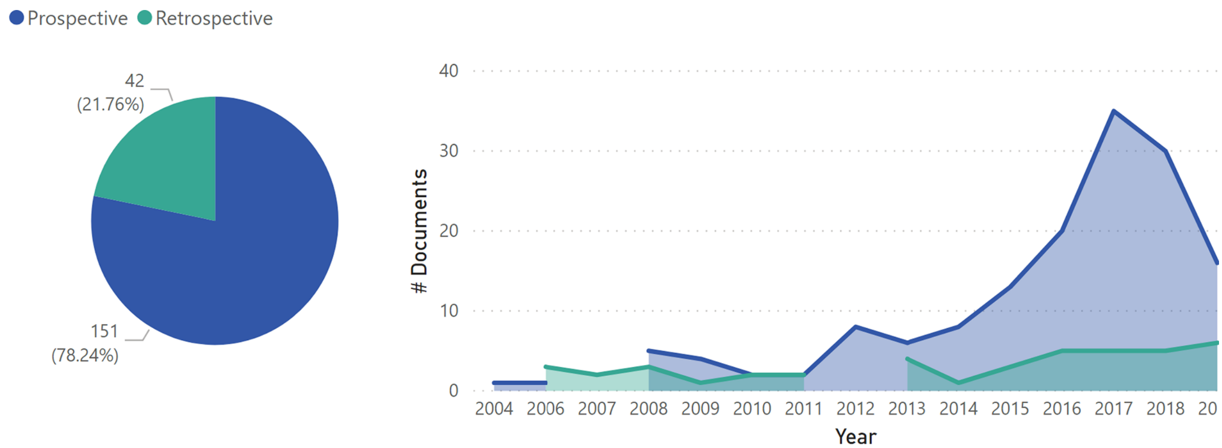


Fig. 11. Perspective adopted for FRAM analysis.

to model system behaviours, and identify or manage system risks. Fig. 11 shows the steady growth of prospective-centred documents, along with a nearly constant use of the FRAM as a retrospective method.

From an analysis of the data collection methods reported in the documents (see Fig. 12, left), it is interesting to observe that questionnaires are rarely used to get information, rather they are largely used in combination with interviews (generally open-ended or semi-structured), which usually have a larger potential to allow the description of complex socio-technical domains (Patton, 2002). Furthermore, there is common evidence that procedures, manuals, protocols, etc. are considered more or less equally frequently as observations and interviews. This is an interesting outcome, considering the FRAM usage to describe variability of work, i.e. WAI: Work-As-Imagined (or more precisely as-prescribed) and WAD: Work-As-Done (or as-disclosed, as-observed) (Moppett and Shorrock, 2018). This analysis also shows the need for triangulation of multiple data collection techniques when performing a complete FRAM analysis: about 30% of the documents use just one data source, less than 20% two of them, and more than 50% adopt three or more different data sources (Fig. 12, right).

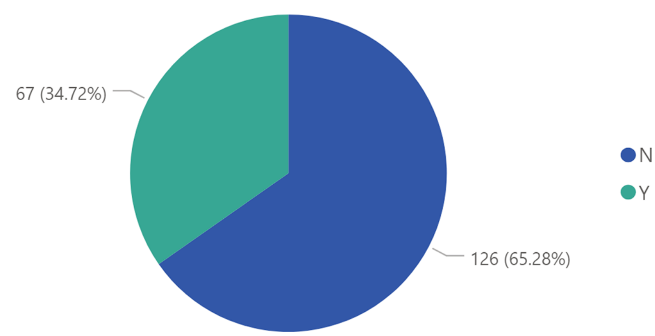


Fig. 13. Presence of changes to the standard FRAM method.

As a last descriptive analysis, the FRAM application suggested a relevant focus in the modification, revision, and evolution of the

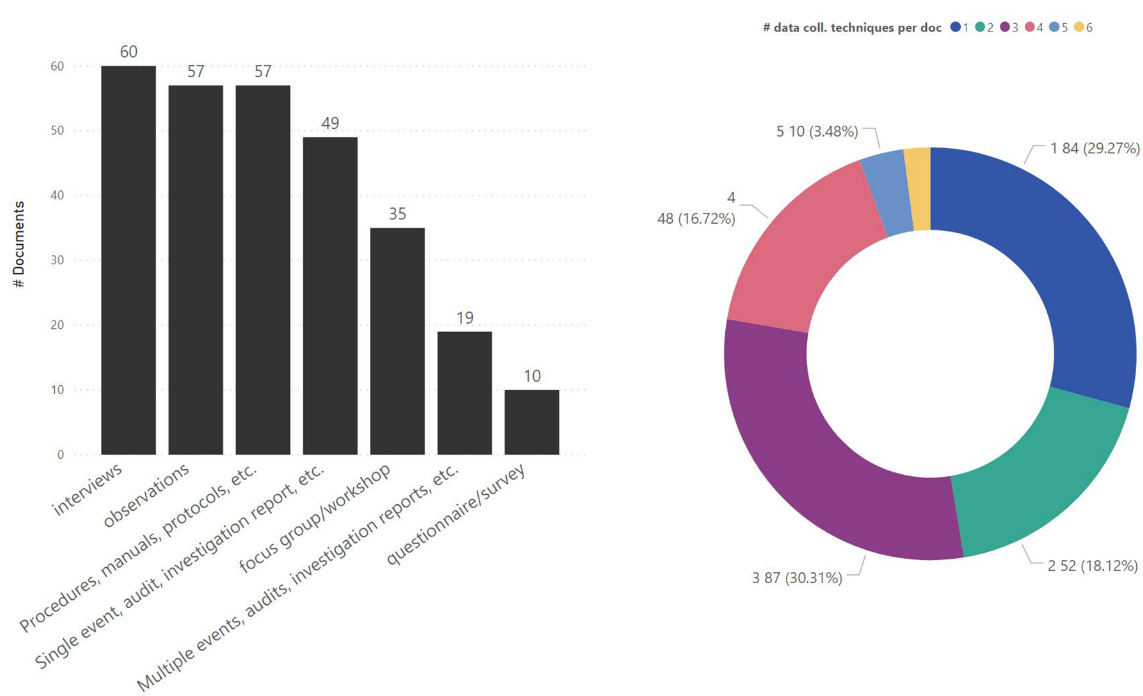


Fig. 12. Data collection methods in FRAM applications.

standard FRAM method by Hollnagel, respectively (Hollnagel, 2004; Hollnagel and Goteman, 2004) or (Hollnagel, 2012) (see Fig. 13). A detailed analysis of this result is discussed in Sections 4.3-4.4 where the FRAM is described as used in a revised version, and/or as a part of a bigger methodology.

4. Interpretative results

This section presents the interpretative results obtained from the analysis of the documents included in the final dataset. It is worth highlighting the epistemological motivation for consciously adopting the term interpretative in this regard. This decision was made to point out that the authors of this research had to interpret the published papers in terms of the categories created for the review, and as FRAM studies describe complex socio-technical analyses, some interpretation was necessarily required.

4.1. FRAM for retrospective analyses

FRAM applications for retrospective analysis aim at unveiling potential systemic failures or critical underlying elements of specific work domains. Generally, such FRAM investigations start from the reporting and/or auditing of events in order to understand how an adverse outcome propagated, and how its causes or effects were dampened or amplified throughout the socio-technical system.

- Transport

From 2006 to 2010, all the contributions included in this review focused on exploring advantages and disadvantages of the FRAM, in particular in the aviation domain. The first example is the analysis of the Alaska Airlines flight 261 accident (Woltjer and Hollnagel, 2006). The airplane pitch control was lost as a result of the in-flight failure of the horizontal stabilizer trim system jackscrew assembly's acme nut threads. The FRAM accident analysis described a wide range of human, technical, and organizational factors contributing to the event. The same authors further developed their application on the same case study (Woltjer, 2009; Woltjer and Hollnagel, 2007). Other aviation incidents investigated through the FRAM were: (i) F-GRMC on approach to Paris-Orly on 23 November 1997 (Nouvel et al., 2007); (ii) Comair Airlines (Delta Connection) flight 5191 in Lexington KY on 27 August 2006 (Hollnagel et al., 2008); (iii) Norwegian Air Shuttle Boeing 737–36 N NAX541 en route from Stavanger Sola to Oslo Gardermoen on 9 February 2003 (Herrera and Woltjer, 2010).

Afterwards, other researchers have continued to apply the FRAM for retrospective analyses in the same domain. The FRAM was used to show the key resilience characteristics of an Air Traffic Management system through the investigation of the mid-air collision between flight GLO1907, a commercial aircraft Boeing 737–800, and flight N600XL, an executive jet EMBRAER E-145, in Amazonian sky on 29 September 2006 (de Carvalho, 2011). The study showed that under normal variability conditions the ATM system did not succeed in closing the control loops of the flight monitoring functions, with neither feedback nor feedforward strategies to achieve an adequate control of the aircraft flying in the controlled air space. Furthermore, the method has been used to evaluate performance in aircraft on-ground de-icing operations and related issues that might endanger flight safety (Slim et al., 2018a). The complex work environment of de-icing operations requires continuous performance adjustments to cope with the dynamic work conditions. De-icing was modelled to analyse the SAS flight 751 crash at Gottröra in 1991 and show how safety issues could arise through the combination and accumulating functional variability. Similarly, the FRAM has also been used for studying the 2015 Barcelona Airport where a Boeing 737–800 was lifted by the airbridge while disembarking passengers (Messana, 2019), and for modelling a runway incursion incident in a large European airport, which involved an Airbus A310 and a military Hercules (Bosse and Mogles, 2013).

In 2011, the first application of the FRAM in the maritime domain was published (Praetorius et al., 2011). The article presents a re-analysis of the Harald of Free Enterprise, that capsized about 20 min after leaving from Zeebrugge. Although the shipping company was considered partly accountable, the original investigation based its result on a rather individual-centred dimension. As for other case studies, i.e. the catastrophe of Cruiser Eastern Star in 2015 (Wang et al., 2017) and the Sewol ferry accident (Kee, 2017), the FRAM analysis provided a deeper understanding on how functional resonance may have arisen, emphasizing the system's weakness and suggesting proactive countermeasures.

The only contribution in the railway domain refers to the accident analysis of a dangerous goods transportation, where the authors focus on the changed in functions' outputs occurred in the event, against normal working conditions (Huang et al., 2019).

- Healthcare

In 2010, the FRAM has been applied to the first healthcare case study for the purpose of an incident investigation where surgical materials were left in a patient's abdomen during a surgical procedure (Alm and Woltjer, 2010).

- Industrial operations

Komatsubara applied the FRAM to investigate the effects of human behaviour on industrial operational accidents (Komatsubara, 2008, 2006). These early contributions, as well as (Komatsubara, 2014), presented limited added value to the research field as the model was not built with a wide systemic functional perspective, i.e. presenting some questionable definitions of functions.

Other publications demonstrated how a resilience engineering perspective may supplement traditional approaches for industrial safety, according to the lessons learned from the Fukushima-Daiichi nuclear power plant disaster (Hollnagel and Fujita, 2013). Same conclusions were reached by different authors who applied the method to the same case study (Lee and Lee, 2018).

- Oil and gas

A research interest in the FRAM developed in the oil and gas industry over recent years. A simplified application referred to the Macondo blowout accident showed the effects of drift from known procedures (Rajendran, 2016). Another case study presented the Chevron Richmond refinery accident (Yousefi et al., 2019), also in comparison with other methods, as fully discussed in section 4.5.

- Other

Minor areas of application refer to road safety management, as for the case study in Myanmar (Hlaing et al., 2018), and the collision between an Uber vehicle and a pedestrian wheeling a bicycle in Arizona (USA) Stanton et al. (2019).

The FRAM has been used to analyse eight coal mine accidents (Qiao et al., 2019) and three constructions harmful scenarios (Amorim and Pereira, 2015) identifying how performance variabilities may accumulate to generate functional resonance.

4.2. FRAM for prospective analyses

The FRAM has been used for prospective analysis from 2004 onwards with the majority of publications between 2016 and 2019. The review identified publications across multiple domains, investigated through different data collection techniques. The following sub-sections present the major research domains investigated through the FRAM.

- Transport

The first record of the FRAM in transportation dates back to 2004 with an analysis of an area navigation (RNAV) approach operation in aviation (Hollnagel and Goteman, 2004). Considering the increasing number of early contributions in this area, it is fair to say that aviation played a key role in the evolution of the method towards a system modelling tool, rather than one singly focused on accident investigation. The large majority of attention has been devoted to issues related to air traffic management, used also as an exemplar domain for conceptual research (Stogsdill and Ulfvengren, 2017). In particular, EUROCONTROL (2009) proposes an early resilience engineering framework for Air Traffic Management (ATM), within which the FRAM is put forward as a tool that may provide valuable guidance towards improving resilience. In this case, the FRAM is described as "Functional Resonance Assessment Method", even before Hollnagel's handbook was published in 2012. More or less contemporarily, other research aimed at developing indicators for managing variability in every day operations (Herrera et al., 2010), and for issues related to Minimum Safety Altitude Warning Systems (MSAW) (Macchi et al., 2009). Still linked to the variability of everyday work, other research investigate potential antecedents and consequences of a mid-air collision (De Carvalho and Ferreira, 2012), or the adaptability of air traffic controllers in daily operations in response to potential threats (Karikawa et al., 2019). Only two documents, i.e. (Adriaensen et al., 2017; Mawhin et al., 2011), more directly address cockpit and flight operations. Cockpit transformations with focus on automation are highlighted as critical issues to be addressed, for which the FRAM may provide relevant support.

The description and analysis of interdependencies is one of the main focuses in the domain, particularly within the frame of risk analysis needs. The FRAM is frequently put forward as a suitable approach to automation and complexity related issues that emerge from its increased presence in aviation operations, as addressed by (Woltjer and Hollnagel, 2008).

Within maritime transport, the FRAM has been applied to offshore operations (Bahoo Toroody et al., 2016a), ice navigation (Smith et al., 2018a), operational design (Clarke et al., 2017; Smith et al., 2018b), and to understand the complex interactions between ship and shore services (De Vries, 2017; Praetorius et al., 2015; Praetorius and Kataria, 2016; Sjölin, 2013). The applications primarily highlight the method's potential to explore underlying mechanisms for system performance and visualise the overall complexity of maritime socio-technical operations. As highlighted by Clarke et al. (2017), Sjölin (2013), Smith et al. (2018a), the method has a potential of informing future design decisions, as well as to make contributions of system actors to maritime safety salient (De Vries, 2017; Praetorius et al., 2015).

The rail sector has so far registered little use of the FRAM. Belmonte et al. (2011) focus on the integration of human factors with technology change in rail traffic management. From this perspective, the publication addresses challenges like the ones faced in aviation about the impacts of increased automation.

- Healthcare

The FRAM has been applied in the healthcare domain since 2012. The benefits of the method application highlighted by the authors include several features typical of care delivery (i.e.) the possibility to identify differences between WAI and WAD, (e.g.) (Damen et al., 2018; Li et al., 2019; Nakajima et al., 2018; Schutijser et al., 2019) the potential to highlight essential system functions (Pereira, 2013; Raben et al., 2018b), and provide input to the (re-) design of clinical processes and procedures, (e.g.) (McNab et al., 2018; Ross et al., 2018). Furthermore, several articles emphasise the method's potential to visualise how hospital frontline personnel is forced to adapt to the current work context in which resources are limited and the preconditions of work might not be ideal, (e.g.) (Hounsgaard, 2016; Jatobá et al., 2018). A large research interest is linked to differentiation between the conceptual value of clinical guidelines and the operational setting of their implementations (Clay-Williams et al., 2015). This aspect has been specifically discussed also for the drug administration process and radiopharmaceutical dispatches (Pereira, 2013).

- Industrial operations

A common theme across publications referred to a subset of industrial operations (i.e. nuclear operations) is the aim to understand resilience in operations stands out. Lundblad et al. (2008), for example, mention the potential of the FRAM to fill the need of a systemic and qualitative approach to Human Reliability Analysis, while Hollnagel (2013) emphasizes the suitability for exploring organizational change. In line with publications in the maritime domain, Macchi et al. (2012), Oedewald et al. (2012) focus on making complex interactions salient to understand requirements for successful plant performance. Only one publication in non-nuclear power plants was identified: the authors use the FRAM to identify variability in operations for risk assessment from a Safety-II perspective (Portela et al., 2017).

Besides nuclear operations, other industrial plants have been investigated through the FRAM. Waefler et al. (2016) focus on understanding the manufacturing, planning, scheduling and control network in process industries. Similar to healthcare applications, the obtained model enables groups of stakeholders to gain a deeper understanding of functional dependencies, as well as providing a basis for future process improvements. This results is in line with findings in (Melanson and Nadeau, 2019), referred to chassis assembly production department, or the variability investigation in manufacturing companies (Albery et al., 2016). It is also included in this context an early attempt to extend the human error concept through the FRAM principles for lifting accidents in offshore operations (Bahoo Toroody et al., 2016b).

- Oil and Gas

In this domain, the method is primarily used for the purpose of resilience management in operations. Documents are balanced between FRAM-based risk assessment approaches (Abaei et al., 2017; Halseth, 2012; Tveiten, 2013) and wider system modelling approaches (Cabrera Aguilera et al., 2016, 2014). These latter used a combination of ergonomic field studies and the FRAM to explore complexity and resilience in oil spill response capabilities in Brazil, inherently requiring intentional sharp end adjustments. On the other hand, Halseth (2012) uses the method to model the causes of a process leakage: while a clear need for quantification is highlighted, the FRAM is found useful for increasing the system understanding. A similar result has been obtained by Tveiten (2013) who applied the method to a risk assessment at an organizational level. The advantage of being able to assess risk in everyday work, which normally is not provided in traditional risk assessment approaches.

- Other domains

The construction industry is seldomly addressed through the FRAM: one research stream is here linked to discuss a lean approach in conjunction with the use of the FRAM as a tool to understand complexity related issues (Saurin, 2017, 2016). More specifically, Saurin and Sanches (2014) develop a dedicated resilience engineering framework.

Besides the growing interest and research investment registered in recent years around resilience of critical infrastructures, it has produced little impact in the main trends of FRAM applications. The only two articles in this area (Anvarifar et al., 2017; Tan et al., 2017a) discuss FRAM applications on risk and resilience management, emphasizing complexity and interdependency issues. In particular, Anvarifar et al. (2017) describes the usage of the FRAM to investigate the combination of flood protection structures with urban facilities.

Additionally, the FRAM has also been applied for scenario-based training in the debriefing of power grid operator trainees (Wachs et al., 2019). For product design, Pazell (2018) addresses human-centred design within road construction and maintenance work. This research uses a FRAM-based approach to integrate machinery, task and organizational design requirements. Furniss et al. (2016) and Slim et al. (2018b) focus more on the use of the FRAM to capture WAD and drive organizational improvements. Nomoto and Slater (2018, 2017) address cognitive and neurologic aspects by using the FRAM to model brain functions. These articles are very much grounded on exploratory reasoning, but nevertheless produce several relations between brain functioning and certain human performance and behavioural aspects. Slim et al. (2018b) use the FRAM to investigate how performance variability may impact on delay attribution. While aiming to extrapolate to different domains, the article focuses on graduate students and on the multiple supervisory and university related factors that may also impact on overall performance variability and generate delivery delays. Bridges et al. (2018) explore how hunting accidents may occur in relation to the misidentification of targets. The FRAM is used to model deer hunting activities and generate prospective safety improvements. An early attempt of FRAM usage to be mentioned refers to modelling financial services systems (Sundström and Hollnagel, 2008), while more recent research is aimed at software development (Tan et al., 2017b; Werfs, 2015).

Lastly, offering cross-domain perspectives on the usage of FRAM as a prospective analysis tool, other documents aim to explore its potential implications for HRA (Alvarenga et al., 2014), its role to support a regulatory framework for safety (Gao et al., 2019), or even its uncertainty management dimension (Bjerga et al., 2016).

4.3. Change of the method

The literature review reports many attempts to modify the FRAM, trying to facilitate or extend the application of its different steps. A first analysis of these contribution shows two main categories: qualitative and quantitative changes, according to the nature of the proposed modification.

- Qualitative changes

From the very beginning, different research groups developed many contributions that can be summarised into two main clusters linked to the first two FRAM steps, i.e. to identify system functions, and to define functions' variability.

The first cluster recalls a common methodological support that many users experience: a support in identifying, defining and better organizing the functions. A natural evolution of the method sketched early in 2007 consists of exploring the fractal nature of the FRAM to different layers of granularity: "[…] the need to take into account the interactions between different components […] calls for a rearrangement of these components in various layers […]" (Nouvel et al., 2007 - page 8). Such theoretical point has been further developed identifying groups of functions according to different levels of abstraction, starting from Rasmussen's Abstraction/Decomposition framework (Rasmussen, 1985). On this path, some scholars expand such framework defining the functional resonance analysis space through the Abstraction/Agency framework (Patriarca et al., 2017a) and further test such evolution on a case study in maritime operations (Patriarca and Bergström, 2017). Consequently, an analogue conceptual framework has been implemented as well in the latest version of FMV, see (Hill, 2019). Such framework has been further used in conjunction with Cognitive Joint Systems theory, to support the identification of functions, couplings and variability for the process of speed setting in an aircraft cockpit (Adriaensen et al., 2019). All these scholars go beyond Rasmussen's traditional framework: the Agency dimension relates different abstraction levels to identified system agents, in line with the principles of Work Domain Analysis (WDA). A previous similar attempt is an application to the process of commanding and controlling military or civilian units using three different layers, or resolutions, of functions (Prytz, 2009; Woltjer et al., 2009). A similar approach is also the integration of the FRAM with the Actor Network Theory (ANT) to analyse the radicalization process in terrorism (Masys, 2018).

Another detailed solution has been proposed for the integration with the Accident Causation Analysis and Taxonomy (ACAT) model. This latter is presented as a formal support for the limitations on function identification and interaction analyses, which traditionally strictly rely on the experience of the analyst and do not include a fully consistent or explicit stop rule. The ACAT can indeed be used to enrich the FRAM by generating functions based on a closed-loop control system. The case study on operation processes in hazardous industries shows that more functional constraints and deep contributing factors to accidents can be identified with this hybrid approach (Li et al., 2019). Finally, a tentative attempt to define a protocol and automate the identification of couplings was set up, using the Matter Energy Information (MEI) framework (Moskon et al., 2019).

The second cluster of qualitative changes supports the characterization and aggregation of functional variability. Principal contributions start with the description of a specific type of aircraft accidents, the "automation induced surprises", generated by autopilots (Sawaragi et al., 2006). In this FRAM model, 11 Common Performance Conditions (CPCs) that can affect human performance are defined, in line with the FRAM approach initially described in (Hollnagel, 2004). The same approach with CPCs has been tested on the already mentioned Alaska 261 accident, along with an interpretation of the results through Resilient Systems properties by Woods (Woltjer, 2007), and on evaluating organizational competence in human factors and UX (user experience) in web design and safety–critical systems projects (Furniss et al., 2018). This latter document shows how managing personal competences is essential for a project's success, unveiling implications for addressing careers, project tactics and organizational strategy. A similar analysis has been conducted in the PhD thesis of the same manuscript's first author along with Distributed Cognition Analysis to improve the identification of functions and couplings (Furniss, 2008). An extension of CPCs is the introduction of Performance Shaping Factors (PSFs), with a first example in the discharge of elderly patients to primary health care (Laugaland et al., 2014). In the research, PSFs help to describe variability and at the same time support the identification of functions on different levels and agents, tailored on the specific case study.

Another case study, which applies a simple modification of standard phenotypes of variability, is the evolution of Processing, Exploitation and Dissemination in the US Army: gaps and recommendations about force structure and future R&D priorities are identified to increase the throughput of the intelligence enterprise (Danczyk et al., 2016). An attempt to integrate the Anticipatory Failure Determination method (a creativity method) in the FRAM allows substituting the analysis of variability by inventing possible instantiations in which the function gives an adverse output, potentially a failure. The use case in industrial operations is not presenting enough details to confirm the extent of the framework, as it seems to require a cause-effect logic apparently Safety-I oriented (Jensen and Aven, 2017). On a similar conceptual idea but adopting a wider systemic perspective, Guo et al. (2017) produce the FRAM-CS, an approach including an additional step dedicated to the generation of possible propagations of variability within the system as instantiations.

In addition to the above-mentioned two steps, the only qualitative contribution to support step 3 of the FRAM is the integration with the Resilience Analysis Matrix for reconstructing the actual instantiations of an event as well as for analysing possible instantiations in future behaviour of a system. Both applications were presented with reference to the Swedish civil crisis response missions to the Asian Tsunami of 2004 and the Israel-Lebanon war of 2006 and the already mentioned Comair Flight 5191 accident of 2006 (Lundberg and Woltjer, 2013). Lastly, a recent contribution encompasses the possibility of having a heptagonal representation of FRAM functions: a “communication” aspect is provided in addition to the six standard aspects (Pietreanu et al., 2018).

- Quantitative/semi quantitative

Many authors have tried to evaluate the value of performance variability that can arise from the different instantiations of a FRAM model quantitatively (or at least semi-quantitatively).

The first contribution is related to the definition of a variability score accounting for the CPCs’ effects and damping/amplification coefficients of couplings. This method is applied in a safety assessment of the Minimum Safe Altitude Warning by the German Air Navigation Service Provider, Deutsche Flugsicherung (Macchi, 2011). Despite the limited analytical effort, this research paved the way to many different evolutions of the FRAM, as for the analysis of near-miss incidents of train manoeuvring and operations (Fukuda et al., 2016).

Other documents include ad hoc analytical models addressing the quantification of variability for specific safety issues, i.e. organizational mechanisms of coordination and communication among multiple agencies in response to natural disasters (Mohamed and Qu, 2013; Qu et al., 2015); a surgical incident (Wu et al., 2015); forging operations (Gattola et al., 2018). Other researchers have attempted to integrate FMEA in the FRAM to evaluate functions’ criticality, even if referring to a traditional Safety-I model for a use case in a temperature control for smart building (López et al., 2016).

Additional extensions propose an integrated analytical formulation: (i) the integration of SHERPA to combine the Human Reliability Analysis for emergency management in a petrochemical company (De Felice et al., 2017); (ii) the integration of the Resilience Analysis Matrix applied to the runway incursion happened in February 1991 at LAX airport through an algorithm for semi-automated scenario analysis (Patriarca et al., 2018a).

Within analytical modelling, a stream of quantitative research related to Multi Criteria Decision Making (MCDM) techniques arose over the years, considering their utility in situations involving multiple objectives, various decision-makers, and the simultaneous treatment of complex pressures. The FRAM-AHP investigates the relative importance of criteria and alternatives used for the identification of phenotypes of performance variability, as well as the aggregation of variability. After a first application in occupational risk assessment (de Carvalho et al., 2016), the method has been tested in construction sustainability (Haddad and Rosa, 2015; Rosa et al., 2015). Sustainable construction is a tightly interconnected work domain, involving various stakeholders and resulting in situations that remain largely underspecified in procedures, constantly subjected to dynamic operating conditions and variable demands. The FRAM-AHP describes and evaluates how couplings may combine and induce unexpected outcomes. The methodology has been further tested in a case study during the modernization work on the Maracanã stadium in Rio de Janeiro (Rosa et al., 2017). The purpose of this study has been to quantify the variabilities that may lead to occupational or environmental accidents and to provide new recommendations about how work processes should function, minimizing production losses, incidents and accidents. A similar application is also presented for the drilling activities of the oil and gas industry (França et al., 2019). Aligned with this research, the Q-FRAM extends and operationalizes the qualitative concepts of functional variability and dampening capacities. The Q-FRAM proposes a method in which key performance indicators are derived from the model and aggregated into four indicators representing resilience cornerstones (anticipate, respond, monitor, learn) through a MCDM bottom-up hierarchical approach. The four indicators are composed in a unique system resilience index that expresses the total variability at an instant (Bellini et al., 2019). The Q-FRAM exploits another technique that is frequently used to weight interactions and couplings, evaluating the variability of performance: fuzzy logic. In particular, fuzzy CREAM applies the fuzzy logic to the weight the relative impact of CPCs, as presented in the case study of a 1995 accident near Cali Airport (Colombia). The case study shows how the deviation of SOPs started and grew in the cockpit, eventually leading to the fatal accident (Hirose et al., 2017, 2016). The same approach has been tested in an aircraft de-icing simulation with fuzzy logic applied to CPCs (Slim and Nadeau, 2019).

Another main area of research is the application of Monte Carlo simulation to quantify variability of phenotypes and identify resonant functions through a statistical variability score. This approach has been firstly presented in a runway incursion walkthrough application to highlight critical paths among air traffic control functions, and to facilitate safety assessment in different operating scenarios (Patriarca et al., 2017b). This semi-quantitative definition of variability has also been tested in a case study of an environmental evaluation for a sinter plant (Costantino et al., 2018; Patriarca et al., 2017c), as well as in space mission safety requirement analysis (Patriarca et al., 2016), and in protection of offshore wind farms (Kopke et al., 2019). Monte Carlo simulation has further been combined with other qualitative modifications of the FRAM, as for Abstraction/Agency and Resilience Analysis Matrix. Case studies that show such results refer to railway accident modelling (Patriarca et al., 2017d) and the definition of leading indicators in neuro-surgery (Patriarca et al., 2018c).

Other attempts to simulate the behaviour of a whole FRAM model, according to a probability distribution of the different functions’ states refer to a home computer network (Slater, 2013), the Clayton Tunnel rail crash (Slater, 2016) and a moving tram through an urban environment (Smoczyński et al., 2018).

Another promising contribution is the expansion of the FRAM by means of formal verification. The approach focuses on modelling of system functions, formalization of functional variability and interactions, and verification whether the pre-set safety requirements are violated. The first attempt of formal verification is the FRAM-MBSA, demonstrated through the analysis of the landing process as for the Flight Crew Training Manual (Yang and Tian, 2015). The same authors propose the SPIN tool, applying the approach to a developing air traffic management system. The analysis refers to the introduction of the Minimum Safe Altitude Warning and it illustrates how multiple locally small variability (e.g. linked to surveillance data and terrain conflict alert confirmation) brings large effects to global system performance (Yang et al., 2017). Such approach is still applied to limitedly sized models, due to its large computational efforts.

4.4. FRAM as part of a bigger methodology

This section discusses the approaches where the FRAM has been used in combination with other methods or extended into a wider methodology than the FRAM alone. The results are presented mainly grouped by qualitative and (semi) quantitative approaches, with the purposes of incident/accident, risk and system modelling and analysis, broadly per domain of application.

- Qualitative approaches for accident, risk and system analysis

Several studies in the transportation domain use the FRAM as part of a risk assessment methodology. In a series of related works (Martinie et al., 2013, 2012; Pasquini et al., 2013; Ragosta, 2015; Ragosta et al., 2015; Rigaud et al., 2012), a FRAM-based methodology is provided as a risk assessment method, integrating Human-centred Assessment and Modelling to Support Task Engineering for Resilient Systems (HAMSTERS), ICO, and PetShop. The FRAM instantiations help to generate “concept maps” for aviation settings. Still in the aviation domain, the (Hybrid) Total Apron Safety Management (TASM) framework (Studic et al., 2017; Studic and Majumdar, 2015) combines the FRAM with Grounded Theory, Template Analysis and Goals-Means Task Analysis (GMTA). More in the air traffic management area, the AUTOPACE methodology (Ferreira and Cañas, 2019) incorporates the FRAM into a risk assessment method for increased automation management. In the same domain, another method for risk analysis of everyday work combines the FRAM with SHA and HAZID (Frost and Mo, 2014).

In rail transport (Farooqi, 2016), a wide application of methods has been used to characterize the specific domain of railway accidents for risk assessment combining FRAM (using the FMV tool) with Cognitive Task Analysis. Two further railway domain papers draw on a FRAM analysis of a single event in their data collection: first, a six step process with time-based analysis (Liu and Tian, 2017) where the authors use a combination of the FRAM and risk assessment matrices with the purpose of resilience management; second, the "dissonance engineering" approach is defined to explore dissonance visualised in an integrated matrix (Ruault et al., 2013). Both documents apply the FRAM up to step 4 as part of their own bigger methodology. A risk assessment method using task analysis and the FRAM as part of the formal safety assessment has also been developed in the maritime domain (Praetorius et al., 2016).

The FRAM has also been used as part of a bigger methodology in healthcare. A risk assessment method in healthcare enables the analysis of everyday work with a six-step leading indicator identification method (Raben et al., 2018a, 2017), of which the first four steps are the four steps of the FRAM performed using the FMV. Value stream mapping with process analysis and improvement has been combined with the FRAM for risk assessment and systems modelling in healthcare applying the method on everyday work (Rosso and Saurin, 2018; Saurin et al., 2016, 2018).

The FRAM has been used to raise questions about the work domain in a risk assessment method for process plants, in combination with risk matrices and WAI/WAD analysis (Albery, 2014; Shaki, 2017), as well as for process plants' qualitative risk assessment starting from SoK (Bjørnsen et al., 2018).

In urban planning, the FRAM has been applied to everyday work in a methodology for resilience assessment and a quantification approach combining the FRAM with Semantic Processing, 4r Feedbacks, City Big Data and Service Aggregator (Harin et al., 2017). The method has been further applied to guideline development in urban planning using the CRAMMSS framework and a mobile emergency app (Bellini et al., 2017).

In the defence sector, work systems have been modelled with a functional model of a Product Service System design process (Settanni et al., 2017). Thenent (2014) uses the FRAM up to step 3 in aviation for system modelling of envisioned system(s) to depict information flow, combined with a range of qualitative data analysis methods (e.g. thematic clustering).

Goals-means task analysis has been used with the FRAM as part of a Constraint Recognition Method (Smith, 2006; Woltjer et al., 2008), where the FRAM up to step 3 constitutes part of the framework itself. Such analysis results in a state space representation as a graphic method for representing the change in state of process variables over time, visualizing behaviour in command and control microworlds.

In construction, the FRAM has been used up to step 3, operationalizing Design-OMAT and EDEEP (Pazell et al., 2016). It has also been used as a security risk assessment methodology, in combination with root cause analysis and vulnerability analysis (Steen, 2019).

At theoretical level, the FRAM has been adopted to describe information technology with system modelling of everyday work, in combination with STAMP into ISHA (Mason-Blakey, 2017). Still following a theoretical dimension, the FRAM has been also combined with contextual design and Cognitive Work Analysis (de Carvalho et al., 2017).

- (Semi-)quantitative accident analyses

The FRAM, up to step 4, has been applied as part of an integrated hazard identification technique also including State Transition Diagrams, model checking, and HAZOP for an aviation safety event (Duan et al., 2015). Tian et al. (2016) applies FRAM up to step 3 to analyse a maritime accident report. The work combines the FRAM with smaller scope model checking algorithms (cf. Section 4.3) as part of a bigger methodology in an approach called FRAMA.

Based on a FRAM analysis (up to step 2) of multiple maritime accident reports, a methodology has been proposed to analyse collaboration by using link types relying on graph theory and by analysing variability in terms of human-system interaction related to functions (Lee and Chung, 2018). The FRAM has been used as a theoretical foundation for modelling a maritime safety event, as part of a larger solution whose used technology is a Finite State Machine and model checking is the realization means (Zheng and Tian, 2015). Such bigger methodology requires the combined usage of FMV and NuSMV.

A method for the investigation of slack resources has been introduced by applying the FRAM up to step 4 in a healthcare setting analysing multiple incidents using a variety of research methods (Saurin and Werle, 2017; Werle et al., 2019). The authors add three more steps to the method, via ad hoc analytical modelling intended to define scores for each function.

- (Semi-)quantitative risk assessment and systems modelling

A group of researchers has attempted to define quantitative risk analyses for the estimation of more accurate human error probability (HEP), integrating the FRAM up to step 3 with Bayesian Network, Noisy OR-Gate Model, SLIM, and ETA (Bahoo Toroody et al., 2017, 2016b, 2016a).

In the process plant domain, a four steps risk assessment methodology has been reported. The analysis presented the FRAM in a preliminary methodological phase and integrated through Finite State Machine and formal verification, resulting in the proposition of a framework with an updated FRAM (Zheng et al., 2016).

In the recently introduced Internet of Things paradigm, a risk assessment methodology combines the FRAM up to step 3 with FMEA and MEHARI approaches (Mock et al., 2017). In the railway domain, the FRAM is combined with System Theoretic Process Analysis (Toda et al., 2018) to define hazards; and it is further extended to define the model functioning, and Finite State Machines to check model criticalities (Thapaliya and Kwon, 2019).

A decision support tool for urban planning has been developed (Bellini et al., 2016) based on the FRAM, the Resilience Decision Support tool (ResilienceDS), which implements an AHP.

In the healthcare domain, everyday work has been modelled combined with incident data using a Human Factors systems model, the Systems Engineering Initiative for Patient Safety (SEIPS) model, to code observations and identify factors influencing blood sampling activities, combined with the FRAM (Pickup et al., 2017), in an approach that models qualitatively first, and then quantifies variability of everyday activities.

A multi-domain approach tested in aviation, railway, process industry, and mining operations integrates the FRAM in a larger framework incorporating a variety of methods for eye-tracking modelling, i.e. advanced statistical analyses, multi-dimensional scaling, and correlation matrix (Arenius, 2017).

In the process plants domain, human error is described with quantifications and calculations, and system failure scenarios emergent from unexpected and erroneous functional dependencies and connections are explored through a simulation model, using the FRAM up to step 3, SLIM, and analytical modelling (Asadzadeh and Azadeh, 2014).

4.5. Comparison with other methods

This section outlines the way FRAM is compared against different methods and tools. Contributions are presented in light of the comparison method, and the context in which such comparisons are discussed.

Some traditional techniques rooted in reliability engineering have been compared with the FRAM.

- Root-Cause Analysis (RCA)

Alm and Woltjer (2010) and Nakajima (2015) contrast the RCA investigation findings of healthcare cases with results obtained from a FRAM analysis. The FRAM is highlighted to offer a better understanding of the complex processes in situ, as well as of the complexity of couplings within the work settings.

- Failure Mode and Effect Analysis (FMEA)

Two articles (Das et al., 2018; Sujan and Felici, 2012) within the healthcare domain address advantages and disadvantages of using FMEA and FRAM as risk assessment approaches. While the FRAM is identified to be more suitable to model and understand complex processes, FMEA can be applicable to identify factors and risks that can later be used as drivers for system changes (Das et al., 2018). Advantages of the FRAM were primarily identified as the visualization of complexity in the function system design, as well as the opportunity to highlight and consider different contextual influences that may impact system performance.

Melanson and Nadeau (2019) present a comparison between a FMECA and FRAM for occupation health and safety management. The findings show that both methods address different aspects important in safety assessment and consequently, their combination might offer complementary perspectives in manufacturing businesses.

- Fault Tree Analysis (FTA)

In a maritime case study (Bahoo Toroody et al., 2016a), the benefits of using FTA and FRAM have been explored. The authors claims the FRAM requires more effort by the analyst but on the other hand, the FTA might not be suitable as sole assessment method for complex human-centric maritime operations. Similar findings are presented in (Praetorius et al., 2016) where FTA and FRAM are compared during the hazard identification phase in a Formal Safety Assessment. FRAM triggered the participants to identify hazards and risk control options related to organizational factors, which were not possible to obtain through the FTA alone.

Additionally, other systemic approaches have been compared with the FRAM.

- Accimap

Accimap is discussed in comparison with FRAM in six publications (Farooqi, 2016; Smith et al., 2017; Stanton et al., 2019; Wang et al., 2017; Watt et al., 2017; Yousefi et al., 2019). These latter tend to directly address accident analysis, particularly (Yousefi et al., 2019), who focus on the comparison of systemic accident analysis methods. A specific case study is used as grounds for a comparison between Accimap, FRAM and STAMP.

In (Smith et al., 2017), three different methods for safety assessments of a propane feed control system have been compared. The authors show that the FRAM can clearly guide the identification of vulnerabilities in the system design, as well as serve to improve how the influence of operators are incorporated in safety assessment approaches. A particular advantage is the ability to use the obtained FRAM model for both prospective and reactive analysis.

- STAMP

The comparison of FRAM and STAMP is relatively frequent in recent literature (Das et al., 2018; Sujan and Felici, 2012; Watt et al., 2017; Wu et al., 2015). Despite the fact that the FRAM is usually linked to resilience engineering, and the STAMP is tightly linked to control theory, these two approaches appear to be often labelled as the most prominent systemic approaches.

The healthcare domain is the one in which such comparison has been developed most frequently, and the majority of cases also includes other methods. The focus of the comparison is usually patient safety and event analysis, aiming to develop a system-based approach and integrate human with organizational factors. In it specific comparison, Halseth (2012) identifies the main difference as STAMP being a systemic method focused on negative outcomes and countermeasures, while the FRAM rather focuses on system performance rooted in a resilience engineering perspective, i.e. (theoretically) not judgemental process variability.

- Organizational Core Task Analysis (OCT)

Macchi et al. (2012) apply OCT to maintenance tasks for nuclear power plants. While the FRAM enables the modelling of tangible activities (i.e. operational tasks), OCT was needed to identify mission goals and critical demands, thus providing inputs into the operational trade-offs faced during outages.

- Other

Further comparisons can be retrieved in a patient safety research for transfusion incidents, where the FRAM has been shortly compared to other models in terms of incident identification, i.e. Skill, Rules, Knowledge, Swiss Cheese Model, Accimap, HFACS, STAMP, SEIPS 2.0 (Watt et al., 2017). Even if partially detailed, the analysis points out that none of the methods proved to be an outstanding one, and further research should still be done in the area.

5. Discussion

This section aims to propose reflections on the review outcomes, putting emphasis on trades-off for the FRAM application in real settings, and paving the way to future research. The section includes also critical reflections on the review approach, and lastly presents an experimental *meta*-FRAM model (i.e. the FRAM method used to develop a FRAM model of itself).

- Results discussion

When referring to prospective analyses, there is a salient increasing number of articles from 2016 onwards, which highlights the applicability of the method to contribute to the understanding of socio-technical behaviours in highly complex work environments. The comparison between WAD and WAI is a core topic across domains, also for retrospective analyses.

Even if the FRAM for retrospective analyses can be considered a largely applied method, there is still a partial limitation. As shown by researchers focusing on comparisons between outcomes from FRAM analyses and other methods (see Section 4.2.1), very frequently such retrospective analyses take advantage of event reports rather than complete analyses of the work domain. Since investigation reports in some domains are usually based on models of work still suffering from Tayloristic or reductionist perspectives, it is argued for the need for developing FRAM-based investigations that should rather focus on normal work, going beyond the specific facts leading to the adverse outcome (or even limiting the data gathering to data obtained through reductionist assumptions). In this view, a FRAM analysis has the potential to generate bookends where second stories on past events can be told (Dekker, 2011). These second stories foster blameless learning from post-mortems, through an understanding of how things work, i.e. (among others) cues that lead people to make observations, contexts for assessment and judgments, things that people know and might assume are common knowledge, signals that bring people to ask for help (Allspaw et al., 2016). Such perspectives are not offered by traditional linear causal analyses, which are usually based on assumption and prospective reasoning, as discussed in human factor literature (Dekker, 2014).

The observed widespread use of FRAM for both retrospective and prospective analyses may partly be explained by the advantages proposed by FRAM-based software, i.e. mainly the FRAM Model Visualiser (FMV) (Hill and Hollnagel, 2016), and at later stages the myFRAM (Patriarca et al., 2018b), which are both openly accessible for users. Starting from 2015, the usage of the FMV in literature spread significantly (after 2014, every year the number of publications roughly doubled), as it is reflected as well in the increase of published studies on the FRAM. Before that date, most FRAM papers adopted custom solutions, mostly drawings or simple schemes produced by the authors themselves. In this context, myFRAM further supports the analysts with a data structure to be used for analytical solutions (e.g. analytical modelling in Excel, usage of simulation frameworks, etc.) (Di Gravio et al., 2019).

The FRAM's spread is also confirmed by industrial involvement in FRAM-based research. It is interesting to observe the balanced values between work with either an active or a passive industrial role (see Section 3.3). This result is encouraging, and it is aligned with the bottom-up nature of the FRAM. Generally, the purely academic documents present theoretical evolutions of the method, which however should be considered as a first step to create usable solutions in real world operations. Overall, the analysis shows balanced values between some type of industrial contribution (more or less same number of documents for active or passive contribution) and academic works.

From the descriptive analysis of institutions' location, the limited contribution of US scholars is unexpected. This effect could be due to the European roots of the FRAM, especially considering that Hollnagel initially developed the method when in Linköping (Sweden), Sophia Antipolis (France) and then extended it in Denmark. Scholars in the US are currently largely focusing on STAMP and its associated techniques, proposed by Leveson from MIT (Leveson, 2004), see (e.g.) (Hulme et al., 2019). Nevertheless, as suggested by the scholars attempting a combination of the logic between the two approaches, there may be room to explore a multi-method approach encompassing and harmonizing respective salient aspects. The fact that FRAMily meetings so far only have been held in the European area has perhaps been a (pragmatic) limitation to FRAM's spreading in other world regions (see Fig. 1). Systematic FRAM training courses have, however, been - and are planned to be - held over the years outside Europe, most notably in Australia. The 2020 edition of the FRAMily to be held in Kyoto (Japan) represents a good opportunity and an encouraging practice to promote FRAM development also in other world regions.

The co-authorship network analysis graphically depicts a good level of networking in the research environment, even if there are many scholars' communities that could be reinforced taking advantage at least of their geographical proximity (see Figs. 8-9). Following this empirical evidence, we hope researchers take the opportunity to acknowledge their common research interests (either if purely methodological, or domain-based) to further promote national and international multi-disciplinary collaborations.

- FRAM application trade-offs

When referring to current FRAM applications, one aspect highlighted across several reviewed contributions is resource intensity. To determine core functions, their couplings, as well as potential and actual variability, access to the work domain and frontline personnel is a prerequisite to ensure ecological validity and fidelity of the model. Such weakness is also an added value of the FRAM itself, if properly motivated by the context under investigation.

While frontline access is hard to get, one of the selling points of the FRAM is that it is an expert-friendly method, encouraging both sharp end and blunt end being involved in a joint process, as proved by the large number of practitioners involved in published literature. Especially for prospective risk or safety management, this feature opens for co-creation and fostering mutual understanding across organizational levels. This understanding may generate opportunities to co-create workplace interventions and provide various stakeholders in a domain with a thorough and detailed system description. It may further increase the understanding of the organizational and contextual factors that facilitate or constrain everyday work in high-risk settings.

While the FRAM shows tremendous potential to be applied for modelling complex work in high-risk domains, it is not a solution easy to implement in modern tightly interconnected systems exposed to constant pressures for quality, safety and productivity, and subjected to resource scarcity (time, personnel, equipment, etc.) (Rasmussen, 1997). In large scale models, the inherent complexity of the system might be transferred to the corresponding FRAM model potentially leading to overwhelming graphical representations, at least if the model is not abstracted at the required level of detail, or if model's boundaries are not adequately set. Understanding the proper granularity level or the positioning of such boundaries is not an easy task. Following a complexity management perspective, there are no clear stop rules for the FRAM, but trading-off the boundaries positioning requires a combination of expertise both in the method and in the application domain.

A trade-off between model's level of detail and systemic vision is one of the main targets for pursuing a robust reality-based safety science research adopting FRAM, i.e. a science where theory is grounded in rigorous observations of existing practice and practice is based on established theory (Rae et al., 2020).

- Future research

The research on the FRAM started approximately 15 year ago. Today we can claim the method is still evolving, accounting for both methodological contributions and traditional applicative research.

On this regard, it could be relevant to introduce semi-automatic data gathering for measuring process variability and unveiling sources of potential resonance to feed a FRAM model.

At a qualitative level, future research on FRAM may further enhance the formal identification of functions and variability through systematic approaches for facilitating method's reproducibility that may take advantage of ontological foundations. An example is represented by the proposal of a seventh aspect for function definition (Pietreanu et al., 2018), i.e. communication. While communication is often critical in socio-technical systems, in the FRAM lexicon it can be modelled as any of the traditional aspects. Therefore, its specific characterization as a different aspect may jeopardize the semantical consistency of model's connections.

More structured attempts to ensure semantical consistency of the method refer to the usage of the Unified Foundational Ontology (UFO), which has the potential to abstract FRAM foundational aspects in lights of the UFO three layers of analysis, i.e. endurants, events, and social agents (Guizzardi and Wagner, 2010; Lališ et al., 2019). The FRAM could also be adopted to explore the role of interactions in socio-technical systems: currently it does not include an explicit taxonomy for interactions except the one referred to phenotypes. Future research can also strengthen such dimension based on a recently introduced taxonomy of interactions for functional modelling (Abreu Saurin and Patriarca, 2020).

Research interest in variability quantification is increasing including fuzzy logic (Hirose and Sawaragi, 2020). Additional time dependent simulative approaches would be beneficial, starting from the concept of functional signatures (Smith et al., 2018c). Research is also focusing on transposing the FRAM methodological framework into the language of network theory, adopting multiplex networks in order not to lose any modelling information (Falegnami et al., 2019). This attempt is aimed at taking advantage of the well-established research on network theory for modelling socio-technical aspects as represented via FRAM models. It is worthy noticing that any model obtained through the FRAM can be used as a basis for other analysis approaches (e.g. agent-based modelling, Petri Nets, system dynamics, etc.). The discussion left to future research refers to explore the extent to which such combined approaches do not fall back into the traps of reductionist mathematical assumptions but remains useful to gather management decisions.

From a domain analysis, it can be noted the growing interest especially in healthcare-related practices (Arcuri et al., 2020; Buikstra et al., 2020; O'Hara et al., 2020; Oduyale et al., 2020), as well as in non-traditional domains, mainly IT and cyber-physical systems, as for recent research on software requirement elicitation (de Carvalho et al., 2020), or conceptual work on Industry 4.0 (Adriaensen et al., 2019).

This tendency is also motivated by the growing interest in Resilience Engineering (and consequently in the FRAM as a representative method) by the IT community worldwide, which is addressing the discipline as "an IT cultural discipline […] to enable always-on and always-available digital business" (Balasubramanian et al., 2018).

- The methodological approach of the review

From a conceptual point of view, scholars recently challenged the hierarchy of systematic reviews over narrative reviews (Greenhalgh et al., 2018). In this paper, the decision to define protocols for the analysis in line with PRISMA was considered necessary to ensure a reasonable level of homogeneity for the analysis, especially in light of the different sub-topics covered by the literature, as well as different backgrounds of the experts involved in the research. The adoption of protocols was also suitable to define a structure for the analysis, which was then integrated through interpretative reflections. On this path, several cross-checks have been proposed to increase the review validity. We combined a systematic search strategy with both *meta*-analytic and interpretative results, conscious of the complementary aspects of narrative and systematic reviews (Greenhalgh et al., 2018).

Due to the extensive nature of this literature review, one can note the large number of documents included in the initial query with respect to the final number of assessed full-text. Many documents were disregarded because they just mentioned the FRAM, usually brought as an example of an innovative systemic method, or even as an exemplar Resilience Engineering tool. The efforts spent to exclude such documents largely coming from Google Scholar unstructured query were needed to make sure that grey literature was analysed, since it plays - or at least, played in the early stage - a relevant contribution to method development.

Besides the inherent incompleteness due to initial database selection, as well as inclusion criteria (in the case of this review, mainly language), any literature review becomes incomplete as soon as it is concluded, for obvious pragmatical reasons related to its timing. Nevertheless, the number of articles reviewed in this paper ensures an extensive conceptualization of the work conducted so far on the FRAM, starting from its very beginning towards the most recent methodological developments and applications.

- FRAM model of the FRAM method

When managing complex socio-technical systems, there is no valid "one-size-fits-all" solution. The FRAM is no exception. The FRAM is an extremely versatile method and it can be used for a wide range of modelling purposes also including abstract concepts, ideas, or even other methods.

As a conceptual summary, it has been applied deliberately here to model itself, i.e. developing a FRAM model of the FRAM method: see Fig. 14, where the blue functions are performed by FRAM analysts (dark

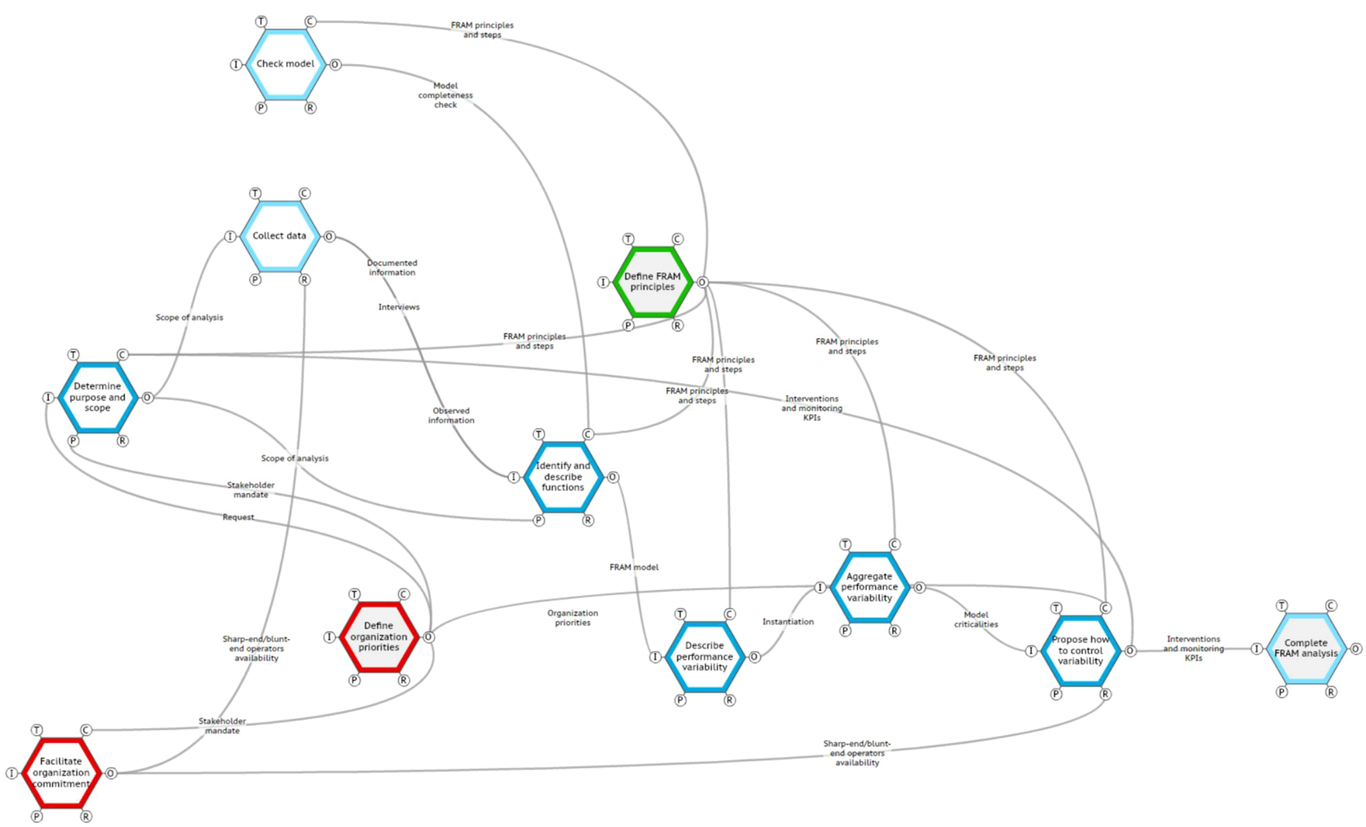


Fig. 14. FRAM model of the FRAM method.

blue are the four building steps, plus the so-called step 0, light blue are additional inherent steps), the green one is an abstract function referred to FRAM theory development (here intended as a background function), the red ones are organizational functions whose responsibility belongs to the company involved in the analysis.

Note that this basic model could be easily expanded, exploring further current background functions (e.g. the definition of organizational priorities may be controlled by the last step of the model) or providing descriptions of some building steps through more actionable phases (e.g. modelling how specific data are collected).

Nevertheless, besides the academic experiment depicted in Fig. 14, the FRAM remains a method to model non-trivial socio-technical systems. As such, it requires a proper motivation for its application, rooted in the complexity degree of the system at hand.

6. Conclusions

Considering the results of this review, we do believe we can summarize our research through a 2013 quote by Nemeth: *"rather than a destination, FRAM is the most recent step […] in understanding complex socio-technical systems"* (Nemeth, 2013). Or even, using Hollnagel's words:

≪ What is in the future for the FRAM? As I see it, a method is always developed to deal with the problems at the time. (This also goes for the more traditional analysis methods that are linked to a specific model.) Since the problems will change, any method – including the FRAM – will sooner or later become outdated and obsolete. No one can say when that will happen, but when it happens there will surely be something to take its place. I will certainly look forward to that. ≫

As demonstrated by this review, the FRAM has been progressively evolved by several researchers who tried to complement, and integrate the original methodological steps proposed by Hollnagel in 2004 and 2012. Even if arguing for the benefit of multi-method perspectives for socio-technical analyses, we think the FRAM remains a promising approach for managing some of the current and future challenges to be faced in modelling complex dynamic socio-technical systems.

Acknowledgement

The research has been partly funded by Sapienza University of Rome through the Fellowship BE-for-ERC assigned to R. Patriarca for his research project "RESCUE" – Resilience Engineering for Safety in Complex Unexpected Events.

Appendix. – Protocol phase 2

This protocol was the basis to define an Excel datasheet. A Note field was dedicated to every item in the protocol, plus a general "note" to overall comment.

- FRAM phases applied/developed:
  - o Up to FRAM step 0
  - o Up to FRAM step 1
  - o Up to FRAM step 2
  - o Up to FRAM step 3
  - o Up to FRAM step 4
  - o Theoretical (no FRAM application)
- Data collection (multiple choices allowed)
  - o Single Event/audit/investigation report (etc.)
  - o Multiple Event/audit/investigation report (etc.)
  - o Procedures/manuals/protocols (etc.)
  - o Focus Group/workshop
  - o Interviews
  - o Questionnaire/survey
  - o Observations
  - o None (envisioned system, or no model developed)
- Size of the FRAM model
  - o Provide number of functions (full model, specify criteria);

  or

o None (no FRAM model developed)
o Unknown (no complete info available)

In case of multiple models (e.g. multiple instantiations, or multilayer representations), define the bigger model size. In case the model size is not available (neither picture provided, nor text description), select Unknown. Select "None" in case there is no FRAM model developed, but it is a theoretical work.

- Do the authors declare any explicit change to Hollnagel standard methodology (relevant for the research, 2012 or 2004)?
  - o Yes
  - o No
- Has the FRAM been developed as a part of a bigger methodology?
  - o Yes
  - o No

Answer "Yes" is the FRAM is just part of a bigger model/method/framework.

- Method or Technique adopted (multiple choices allowed, free text). For example:
  - o Fuzzy logic
  - o Bayesian Network
  - o Monte Carlo Simulation
  - o Network analysis
  - o AHP/ANP
  - o Delphi
  - o …
- Comparison with other methods (multiple choices allowed, free text). For example:
  - o FMEA/FMECA
  - o Accimap
  - o STAMP
  - o STPA
  - o STEP
  - o CREAM
  - o FTA
  - o …
- Industrial Contribution
  - o Active (one or more author(s) from a company - such as an airline or a hospital; or explicitly acknowledged company/employees in the acknowledgements)
  - o Passive (if the industrial involvement in the form of informants - such as interviewees - is just mentioned in the case study)
  - o None (if there is no acknowledgement or involvement from industrial partners)
- (Specific to theses). Indicate faculty and department (e.g.): Faculty of engineering, Department of Mechanical Engineering.
- Software used for FRAM analysis (multiple choices allowed, free text). For example:
  - o FMV
  - o myFRAM
  - o Excel
  - o Visio
  - o Matlab
  - o …

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