Safety Risk Management Methodologies (SRM)

FRAM – Functional Resonance Analysis Method

This document was developed by the Safety Management Panel (SMP). It is intended to support safety experts in the application of risk management methodologies. Any comments to this material should be forwarded to safetymanagement@icao.int.

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1. DESCRIPTION

1.a) Purpose of the method

Originally developed for accident investigation purposes, FRAM can be the basis for analysing events, risks, or system designs in either a retrospective or prospective manner. It is not focussed solely on the failure cases and their causes and consequences, but also on how to understand complex sociotechnical systems in order to improve their resilient behaviour.

FRAM analyses aim to:

- Describe the functioning of a system (i.e., everyday work or a particular event); and/or
- Understand how the different human, technological, and organisational functions behave within a system to achieve its goals, and may be impacted by variability (i.e., variability of a single function or a combination thereof).

Well-known incident analysis methods and accident models that appeared after WW2 (e.g., Event/Fault Tree Analysis, Root Cause Analysis, etc.) initially aimed at explaining or anticipating technical failures in a mechanistic way. This approach was later expanded to human and organisational 'failures' using similar approaches (e.g., Swiss Cheese Model, BowTie, etc.). In contrast, FRAM - along with a few other methodologies that have embraced systems thinking principles - does not seek to lay out all the cause-effect chains within a system in a sequential or rigid way. FRAM analyses aim to be the starting point allowing organisations to develop recommendations on how to monitor and positively influence the inescapable variability of everyday work, especially when dealing with complex systems.

In terms of graphical outputs, FRAM analyses are quickly recognized by their distinctive web(s) of interconnected hexagons, each representing a function within the system and/or the situation that is being analysed (see figures 1 thru 3). FRAM is very different from logic trees or from static engineering diagrams. It is important to realise that FRAM models are not made of hard-wired hexagons connecting system components. Rather, FRAM helps in building a model of dynamic, nonlinear interactions and interdependencies of system functions.

As its name indicates, FRAM is a method rather than a model (i.e., not a template or a mould). However, using the method will eventually lead to an infographic model of the system that is analysed. This 'FRAM model' therefore refers to a specific system. Since everyday work variability produces different system states and outcomes, each active state in a process will have its own FRAM model to show these variations, called instantiations. These instantiations appear as the model is run for the successive steps - or cycles- of a process or activity. Put very simply, instantiations are comparable (but not identical) to the frames of film strips. A detailed FRAM model would typically contain several instantiations for different system states that are displayed one at the time (i.e., one instantiation per system state). Software tools greatly assist in creating a model and its instantiations, and in navigating through them.

1.b) Theoretical basis

FRAM is an analytic tool that evolved from a school of thought on 'human error' and safety management that also fostered Resilience Engineering and Safety-II thinking. More precisely, FRAM is rooted in general systems theory, psychological and cybernetic research, and the principles of structured software development. Erik Hollnagel first published its basic principles in 2004, subsequently incorporated his Safety-II perspective into FRAM, and consolidated its core theoretical elements in his 2012 book (see 4.b for complete references). FRAM is founded on the following four principles:

1. **The equivalence of success and failures –** Tasks or activities generally are covered by rules, procedures, requirements, and "*humans-in-the-loop"*. Outcomes of these tasks or activities may be as "good" as expected or not as good as imagined. No matter what these outcomes are, they happened in very much the same way.
2. **Approximate adjustments –** Daily work performance is influenced by countless factors and always contains some element that was unexpected and/or not covered in company documentation or in training. Consequently, adjustments are inevitable without exception. On the other hand, resources (e.g., information about the system, time, workforce, budget, etc.) are nearly always limited or unreliable in some form. Adjustments that are necessary to achieve system goals will therefore be approximate rather than precise. Such approximate adjustments play a crucial part in why things predominantly go well and occasionally go wrong.
3. **Emergence –** Everyday work variability can manifest itself through the functions of a system and through the approximate adjustments that are made in response. However, the variability in adjustments is rarely large enough to cause significant issues, even if they're approximate. On the other hand, the variability of multiple functions may coincide and mutually affect each other in unexpected ways. This might lead to unexpected and disproportionately negative or positive impacts. The relationship between causes and consequences is therefore no longer direct and proportional, but non-linear. Both good and bad outcomes can then be explained as emerging from variability, rather than as the result of malfunctions or defects in a specific element of the system (particularly human).
4. **Resonance –** Resonance can be observed in one of three possible forms. Classical resonance must be built-up over time and is typically seen through oscillations of physical systems at certain frequencies (e.g., resonance between the cords of instruments, or soldiers marching in step across a suspension bridge, involuntarily leading to increasing oscillations and swaying of the bridge). In stochastic resonance, random noise pushes an otherwise weak or subliminal signal over a detection threshold. Finally, functional resonance refers to the variability of performance in sociotechnical systems (e.g., due to approximate adjustments), thereby allowing to raise the understanding of emergent and non-linear outcomes with a view to increase predictability and control (or at least influence). Functional resonance can be seen as the outcome resulting from the unintended interaction of the everyday variability of multiple functions within a system.

1.c) Method overview

Originally, three types of system functions were identified:

- **Technological –** these functions are relatively stable,
- **Human –** these functions vary with high frequency and high amplitude, and
- **Organizational –** these functions vary with low frequency but high amplitude.

FRAM analyses identify system functions, each represented by a hexagon, followed by an analysis of their couplings, their variability, and by an evaluation of the way in which the different functions interact and influence the way the system behaves. They generally involve the following four steps:

1. **Identification and description of the system's functions**. A system achieves its goal by a series of functions. FRAM describes a function by a verb, or a verb phrase, to indicate what to do. This type of modelling resembles a Task Analysis. For instance, the following steps are essential when making coffee (figure 1): get a recipient, a filter, coffee powder (made at the last minute from beans or ahead of time), boil water, put the powder in the filter, pour the boiling water on the powder, and wait for a thorough percolation. In FRAM, all these activities are seen as functions.

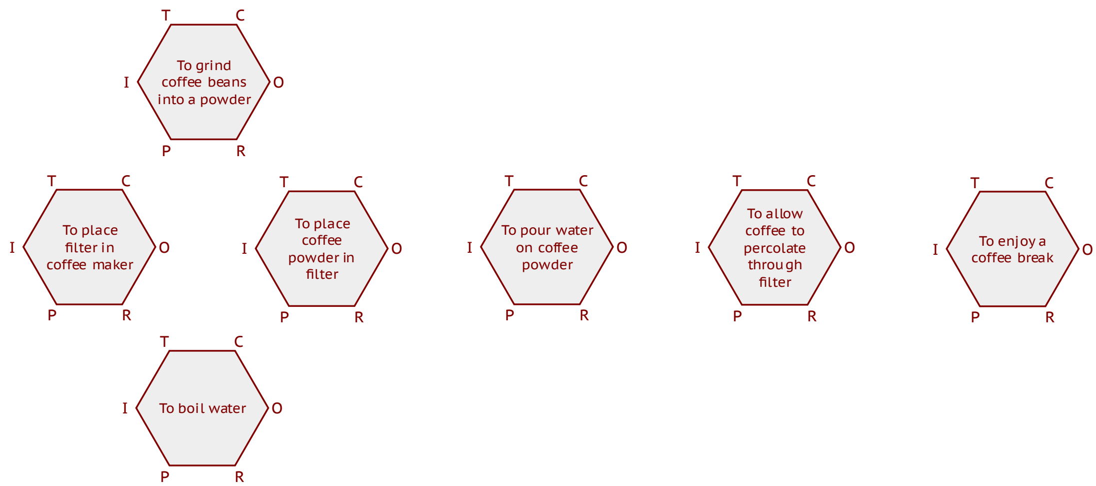


Figure 1 – Functions necessary to brew coffee for a coffee break.

Each function can be affected by interactions and interdependencies with any other function in the system through up to six "aspects": Input (I), Output (O), Precondition (P), Resource (R), Control (C), and Time (T). Note that a letter can be found at each corner of the hexagons and that its position is fixed by convention. Before moving on to the second step, it is necessary to start identifying any coupling between aspects of functions and to draw those interactions as follows:

- Input (I) and Output (O) indicate the start or finish of a task or function. They may represent intent, matter, energy, or information.
- A Precondition aspect (P) refers to conditions that should be in place or to an interaction that is needed before a function is executed. On the other hand, only an Input can initiate or activate the function. In the example with coffee, the Precondition supplies a confirmation of the presence of powder in the filter. This then confirms that the function "to place coffee powder in the filter" has been completed and that the function "to pour water" is ready (or to be more precise, in a state which can now be activated).
- A Resource aspect (R) can indicate the availability of matter, energy, information, software, competence, labour, tools, etc. that will be consumed while the function is carried out.
- A Control (C) can confirm the presence of an active plan, schedule, procedure, a set of guidelines, a program, expectations, etc. that need to be in operation, and actively relayed, to keep the function on track.
- Time (T) can be a special or limiting form of control, related to the temporal relation and sequencing of different actions.

These aspects serve to trigger the sequence of events that constitute the way the system will behave. Their interactions can be thought of as a line of computer code. IF: all the aspects are present and meet expectations, THEN: that function will execute its process, ELSE: wait.

Functions are thus coupled (or linked) through aspects of different functions. These aspects are identified with individual descriptions (e.g., boiling water, filter in place) and can link to any other function in the system that requires the same individual aspect and that shares the same name (e.g., the Output of a single function can be coupled with several other functions - see figure 3).

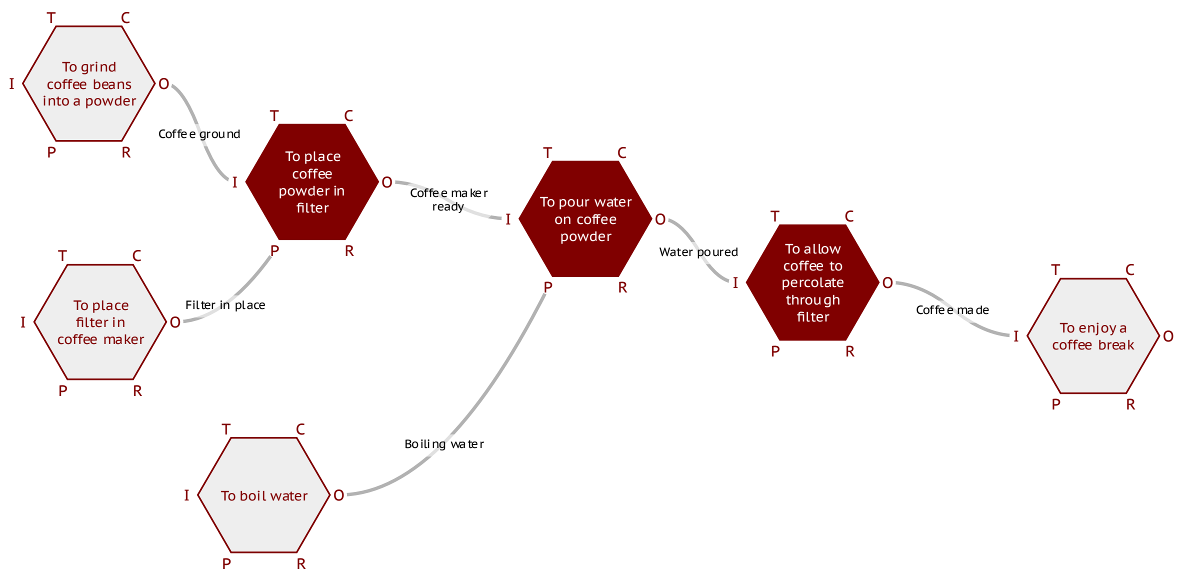
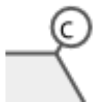
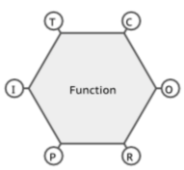
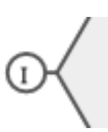
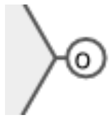
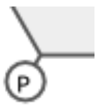
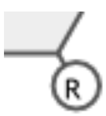


Figure 2 – Functions (to brew coffee) and the couplings between them.

2. **Identification of performance variability**. Performance variabilities are normal in a system. In FRAM, these variabilities are categorized as internal (endogenous) or external (exogenous) variabilities. The former refers to the variation caused by the function itself. The latter is generally impacted by other functions and/or environment, e.g., incorrect readback of the pilot and adverse weather. Originally an output of a function was considered in terms of timing and precision. An Output of a function may occur too early, on time, too late, or not at all. At the same time, it can be described as precise, acceptable, or imprecise in that regard. More precise behaviours of functions can also be defined quantitatively using metadata.
3. **Looking for functional resonance.** Functions are coupled (or connected) with each other in FRAM through the six aspects. Aggregation of variabilities in the functions may cause resonance. Analysing internal and external variabilities helps to understand how upstream functions impact downstream functions, and how things turn out to be. In Figure 2, if the filter is not properly placed (labelled as imprecise), this may lead to the coffee powder and filter falling down when performing the downstream functions. Fortunately, in most cases, we will double check the filter, and make it "go well". If using metadata, the analyst can follow the propagation of variabilities, prescribed or random, using sampling from dedicated distributions.
4. **Management of variability**. System functional resonance may bring positive and negative outcomes. Once the behaviour of the system is sufficiently understood, the basic strategy of managing variability is to amplify the positive effects and damp the negative ones.

1.d) Key terms and definitions used in this document

Term	Explanation
Activity	*"The description of the work that is done (in practice). An activity comprises a number of functions, usually described in the order in which they were carried out."* (FRAM website, 2023)
Aspect (of a function)	Each function (or hexagon) is affected by six aspects: Inputs, Outputs, Preconditions, Resources, Controls, and Time. The presence of an aspect is required to describe the functioning of a system. (adapted from the FRAM website, 2023)
Control (of a function)  	A control supervises or regulates a function so that it results in the desired output. It can be a plan, a schedule, a procedure, a set of guidelines, an algorithm, etc. A different type of control is social control, which can be external (e.g., the expectations of others) or internal (e.g., a kind of self-regulation). (adapted from the FRAM website, 2023)
Downstream functions	Functions that, in a given instantiation of a FRAM model, are logically subsequent to other functions and may therefore be affected by them. The 'downstream' notion is relative rather than absolute since it is impossible to say with certainty whether a function will be carried out prior to or after another function. (adapted from the FRAM website, 2023)
Function  	A function represents the means that are necessary to achieve a goal or produce a certain outcome. These can include what people have to do individually or collectively, what an organisation does, or what a technological system does by itself or in collaboration with people. Each function is affected by six kinds of aspects: Input, Output, Precondition, Resource, Control, and Time. A function is typically represented by a hexagon in graphical renderings of a FRAM model. (adapted from the FRAM website, 2023)
Functional resonance	*"Functional resonance is proposed as a way to understand outcomes that are both non-causal (emergent) and non-linear in a way that makes both predictability and control possible. Functional resonance can more formally be defined as the detectable signal that emerges from the unintended interaction of the everyday variability of multiple signals. The resonance effects that occur can be seen as a consequence of the ways in which the system functions, and the phenomenon is therefore called functional resonance rather than stochastic resonance."* (Hollnagel, 2012)
Input (of a function)  	Traditionally, an input (e.g., matter, energy, information) is used or transformed by the function to produce the output. Its presence or availability serves as a signal to activate or start a function (e.g., an instruction, a clearance). (adapted from the FRAM website, 2023)
Instantiation	*"An instantiation of a FRAM model is a prediction of how a set of functions which are mutually coupled under given conditions (favourable or unfavourable) or for a given timeframe, can combine in a specific sequence to simulate the system's behaviour for that set of conditions."* (FRAM website, 2023)

Term	Explanation
Output (of a function) 	Result of what the function does, for instance by processing the input. An output can represent matter, energy, information, a change of state of the system, or a signal that starts a downstream function. (adapted from the FRAM website, 2023)
Precondition (of a function) 	A function cannot begin before one or more precondition(s) have been established and the aspect is active. A precondition can be understood as system state(s) that must be true, or as condition(s) that must be verified before a function is carried out. It does not itself constitute a signal that starts the function (i.e., this would be an input). (adapted from the FRAM website, 2023)
Resilience Engineering	*"Trans-disciplinary perspective that focuses on developing theories and practices that enable the continuity of operations and societal activities to deliver essential services in the face of ever-growing dynamics and uncertainty. It addresses complexity, non-linearity, inter-dependencies, emergence, formal and informal social structures, threats, and opportunities."* (Resilience Engineering Association website, 2023)
Resonance	*"In physical systems, classical (or mechanical) resonance refers to the phenomenon that system can oscillate with larger amplitude at some frequencies than at others. These are known as the system's resonant (or resonance) frequencies. At these frequencies even small external forces that are applied repeatedly can produce large amplitude oscillations, which may seriously damage or even destroy the system."* (FRAM website, 2023)
Resource (of a function) 	Something that is needed or consumed while a function is carried out. This can include matter, energy, information, competence, software, tools, labour, etc., but typically does not include time, which has a special status and is treated as a separate aspect. (adapted from the FRAM website, 2023)
Safety-I	Perspective that defines safety as a condition where the number of adverse outcomes is as low as possible, and where systems can be in either one of two states: either everything works, or something fails. Safety management efforts therefore focus on finding and fixing 'errors' and on constraining performance, so that systems display minimal variability and don't drift into failure. (adapted from Hollnagel, 2014)
Safety-II	Perspective that defines safety as a condition where as much as possible goes well. Since the people's ability to adjust their activities under varying conditions is seen precisely as the key to ensuring success, safety management efforts focus on understanding everyday activities to recognize, monitor, and control performance variability. (adapted from Hollnagel, 2014) Note: in aviation, the Safety-II perspective is sometimes labelled as "Learning From All Operations" (LFAO).
Stochastic resonance	*"Enhanced sensitivity of a device to a weak signal that occurs when random noise is added to the mix. The outcome of stochastic resonance is non-linear, which simply means that the output is not directly proportional to the input. The*

Term	Explanation
	outcome can also occur – or emerge – instantaneously, unlike classical resonance which must be built-up over time." (FRAM website, 2023)
Time (of a function) 	The time aspect of a function represents the various ways in which time can affect how a function is carried out. Time can typically be seen as a form of control (e.g., in sequencing), as a resource (e.g., in planning), as a precondition (e.g., in a schedule). (adapted from the FRAM website, 2023)
Upstream functions	Functions that, in a given instantiation of a FRAM model, are expected to happen before other functions and may therefore affect them. The 'upstream' notion is relative rather than absolute since it is impossible to say with certainty whether a function will be carried out prior to or after another function. (adapted from the FRAM website, 2023)
'Work-as-imagined' (WAI)	*"Work-as-imagined is both the work that we imagine others do and the work that we imagine we or others might do, currently or in the future. The imagination of human work takes place within organisations, between organisations, and from outside of organisations. To a greater or lesser extent, all of these imaginations -or mental models- will be wrong; our imagination of others' work is a gross simplification, is incomplete, and is also fundamentally incorrect in various ways, depending partly on the differences in work and context between the imaginer and the imagined."* (Shorrock, 2016)
'Work-as-done' (WAD)	*"Work-as-done is actual activity – what people do. It is characterised by patterns of activity to achieve a particular purpose in a particular context. It takes place in an environment that is often not as imagined, with multiple, shifting goals, variable and often unpredictable demand, degraded resources (staffing, competency, equipment, procedures, and time), and a system of constraints, punishments, and incentives, which can all have unintended consequences. Work-as-done is mostly impossible to prescribe precisely and is achieved by adjustments, variations, trade-offs, compromises that are necessary to meet demand."* (Shorrock, 2016)

Table 1 - Key terms and definitions

1.e) Tools available

Many software options have been developed over the years to support FRAM analyses (myFRAM, DynaFRAM, etc.). However, the most widespread is the FRAM Model Visualiser (FMV). It is available as a free web application and can be downloaded through GitHub for installation on a dedicated server (e.g., corporate intranet). The GitHub website also contains additional resources such as source code, extensions, and documentation. One of those extensions is the FRAM Model Interpreter (FMI), which is a systematic model validation tool to verify whether a FRAM model was correctly built and connected in FMV.

The GitHub site also provides access to a more advanced version of the FMV software which allows quantification of the functions, behaviours, and interactions using metadata.

2. User Factors

2.a) Applications

FRAM can serve various roles in both backward-looking and forward-looking system analyses. Arguably, it is also the strongest method to map and compare work varieties, such as the 'work-as-imagined' and 'work-as-done' in daily operations of complex systems, and in turn to identify the gaps between the varieties of work (i.e., work-as-imagined, -prescribed, -done, -disclosed, etc.). This distinctive feature sets FRAM apart from traditional, linear models and tools (e.g., Fault Tree Analysis, Root Cause Analysis, BowTie, etc.). Out of the few modern risk management methods and models rooted in systems thinking (e.g., FRAM, STPA), experience suggests that FRAM is likely the most suitable to model the detailed functioning of systems that are already in operation (e.g., to capture functional relationships within complex systems).

In the context of retrospective analyses, FRAM is not primarily used to deconstruct the event itself, although the establishment of a FRAM model is likely to generate insights related to the conditions and factors leading up to the event. Instead, the FRAM model allows users to portray the operational dynamics in 'normal' operations, when all activities run smoothly and as expected, and usually lead to successful outcomes. Delving into successful execution allows users to:

- Untangle interdependencies between the functions (that are done in each activity);
- Outline the natural variability of these functions; and
- Uncover the factors behind a divergent outcome (e.g., in an incident).

In the context of prospective analyses to outline future or potential activities (e.g., to propose a new procedure or guideline, or to (re)design a system), the FRAM model primarily serves as a tool to uncover potentially crucial linkages between upstream and downstream functions that would not necessarily be identified by linearly modelling the system (i.e., solely through its components). This exploratory work aids in identifying connections and dependencies with significant implications for the proposed changes and their effects on the overall system.

2.b) Use cases

According to a literature review published in 2020, FRAM users span various industries and fields where the understanding of complex systems, risk management, and performance optimization is essential. Although aviation is the industry where FRAM has been applied the most, it is not specifically designed for aviation or for a particular sector of our industry. In terms of numbers of publications, healthcare is the second domain where FRAM has been used the most to model operations in high stress, high hazard situations (e.g., emergency/critical care, quantitative prediction of hospital bed availability, etc.). Other successful applications have been documented in the construction, maritime, extractive, and nuclear industries, among others (e.g., Formula 1 pitstops). Within aviation (see appendix B), FRAM has already been used in various settings (e.g., air traffic control, civil aviation authority, maintenance, ground handling, airline operations control, etc.) and for various purposes (e.g., risk management, accident investigation, operational optimization, research, etc.).

2.c) Users

Considering FRAM is a method of building generic system models, its holistic approach to system design, analysis, and operation, is not meant to provide instant answers or to be a decision aid that frontline workers can quickly revert to when faced with complex problems requiring a rapid response. Instead, the

FRAM is a framework which supports system understanding, analysis and improvement. For example, safety professionals (e.g., safety managers, analysts, and experts) who analyse and manage risks associated with complex systems. Applying FRAM can assist them in identifying potential sources of risk, vulnerabilities, and areas where resonances might lead to undesirable events and system states, such as:

- Human factors and ergonomics specialists working in human factors, ergonomics, and usability engineering to better understand the interactions between humans, technology, and procedures within various systems. Applying FRAM can assist in designing work environments and processes that are aligned with human capabilities and limitations, aiming to enhance performance and reduce errors.
- Process designers and improvement experts responsible for designing and optimizing complex processes within organizations to model functional dependencies, variability, and potential resonances. Applying FRAM can assist in creating more resilient and efficient processes to adapt to changes and unexpected events.
- Change management and decision-making professionals involved in organizational change management and decision support to assess the potential impacts of changes on complex systems. Applying FRAM can assist in understanding how changes might propagate through functions and lead to resonances, in making informed decisions, and in effectively managing transitions.
- Regulatory and compliance authorities to assess and ensure the safety and reliability of complex systems. Applying FRAM can provide insights into potential risks and vulnerabilities that need to be addressed to meet regulatory standards.

More recently, the method has begun to explore producing decision aids, with the ability to utilise external feeds live and historical databases, to follow and predict the way systems will behave under speculative futures (e.g., digital twins).

2.d) Evaluation of complexity

While FRAM can very easily be applied to model mundane tasks (e.g., preparing a cup of coffee), challenges start to appear when confronted with complicated systems and activities involving a web of interdependent functions (e.g., the approach and landing procedures of an aircraft). Although learning the core theoretical principles and terminology of FRAM should be well within the reach of any aviation professional, developing the competencies for accurate modelling initially requires a significant investment in resources. These efforts are likely to be proportional to the complexity of the system(s) considered since meticulous analyses of functional relationships and inherent variability are crucial to adequately capture the complexity and nuances in system design or operation. This being said, the comprehensiveness, usability, and quality of the model obtained will provide insights rarely - if ever - achieved with traditional, linear methods and tools, in particular when modelling complex systems.

2.e) Availability of training

Several resources are available both online and offline. Guidelines, handbooks, recordings of presentations, and manuals can be found on websites dedicated to FRAM (see 4.b – references), often for free. Books (available in English, Japanese, Chinese, and Korean) and scientific articles entirely dedicated to FRAM are also available for purchase through their respective publishers.

Although FRAM can theoretically be self-taught through the resources mentioned above, due consideration should be given to meetings and activities organised by the global FRAM community commonly known as the “FRAMily”. One of its entities, FRAMsynt, is dedicated to providing training on FRAM and organises workshops, courses, lectures, seminars, etc. (see 4.b – references).

3. Quality and Consistency

3.a) Consistency/Differences from SMM concepts, terms, and definitions

Both FRAM and the Safety-II perspective (that underpins FRAM) introduced several new key concepts, terms, and definitions that, to this day, were typically not covered in ICAO publications about safety management. However, there is more complementary than incompatibility between FRAM and the original ICAO framework for SMS. Put differently, the theoretical foundations used in FRAM (and other methods) can shed additional light on how complex systems generally work or should work, produce outcomes, and sometimes fail. From that perspective, FRAM and the literature supporting it complement and expand the existing toolbox of risk management methodologies that are generally better suited to simple or complicated systems where linear causality is the norm. Different models and paradigms have coexisted in safety science for decades. As with other models and tools, there is no universally right or wrong methodology. The key is to identify which is the most suitable and effective to address the specific need(s) of an organisation.

3.b) Validity and reliability of outputs

FRAM focuses on the likelihood that whole functions will vary or resonate, rather than zeroing only on the probability that one or more specific component(s) will malfunction or fail. Therefore, current quantification efforts of functions, behaviours, and interactions, either within FRAM models (i.e., more specifically within the FMV application) or through quantitative or semiquantitative methods (e.g., Monte Carlo simulations) may be challenging to achieve and sometimes difficult to compare with other methods. However, many publications, including peer-reviewed, scientific journals, have confirmed the value of using FRAM in analysing complex sociotechnical systems, identifying hazards, and supporting risk management activities in high-risk industries, including aviation.

To support the validation of FRAM models as being correctly built and connected, an FMV extension called the FRAM Model Interpreter (FMI) is now incorporated into the community edition of the software available on the GitHub site (see 1.e – resources available).

3.c) Overall pros and cons

Pros & strengths	Cons & limitations
• Underpinned by systems theory and fosters a deeper understanding of complex systems. • Core principles are relatively straightforward, but their application from simple through complicated to complex systems should be done progressively. • Can be used reactively (e.g., investigation) and proactively (e.g., system design), but is better suited and more effective with existing systems (i.e., already in operation vs. only at the concept stage). • Effective method for the assessment of performance variability and gaps between the varieties of work (e.g., WAI vs. WAD) • Quantification (e.g., risk probability) is now provided in different extensions to the standard method. • Supported by a global community of practitioners and academics that offers and regularly updates both guidance and IT tools.	• Requires at least an understanding of systems thinking principles. • Detailed system information is needed prior to analysis. • Time-consuming, both to practice and once proficient with the method (e.g., to keep the scale and scope of the analysis consistent) • Representations are not self-explanatory, rather they allow users to better understand the system, and enable the development of mitigation.

Table 2 – Perceived strengths and limitations of FRAM

3.d) Team assessment of usability

Originally developed in the early 2000s to investigate accidents, FRAM evolved into a powerful tool to thoroughly analyse both events and complex systems at all stages of their lifecycle. Being more recent and having slightly less commonality with "basic" engineering principles than other methodologies, the number of publications and guidance to support FRAM implementations is currently not as extensive. However, it has been validated by academics and practitioners as a helpful complement to traditional analysis techniques. Despite its usefulness to understand normal work, its varieties, and the variability of a system's performance, FRAM may not be optimal for tactical risk assessments during high tempo operations (e.g., flight risk assessment tools, flight operations dispatch) or in (very) small organisations. Nevertheless, creating or amending a FRAM model and any instantiation typically generates a wealth of information on the inner workings of a system. This is particularly relevant for complex sociotechnical systems, as traditional methodologies provide very little to no modelling of emergent system behaviours.

4. Additional information

4.a) Abbreviations

Abbreviations	Meaning	Notes
FMI	FRAM Model Interpreter	
FMV	FRAM Model Visualizer	
FRAM	Functional Resonance Analysis Method	
WAD	Work-as-Done	See also 1.d
WAI	Work-as-Imagined	See also 1.d
WW2	World War 2	

Table 3 - Abbreviations

4.b) Literature, references

Diop, I., Abdulnour, G., Komljenovic, D. (2022). *The Functional Resonance Analysis Method: A Performance Appraisal Tool for Risk Assessment and Accident Investigation in Complex and Dynamic Socio-Technical Systems*. American Journal of Industrial and Business Management. Issue 12(02). 195-230

FRAM Website: https://functionalresonance.com/

FRAMily Meetings: https://functionalresonance.com/framily-meetings/

FRAMsynt contact: sensei@functionalresonance.com

GitHub (community software and manuals, open-source code, support): https://github.com/functionalresonance

Hollnagel, E. (2018). *FRAM - the Functional Resonance Analysis Method; A brief guide on how to use the FRAM.*

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APPENDICES

Appendix 1 – Simple FRAM model of an aircraft take-off

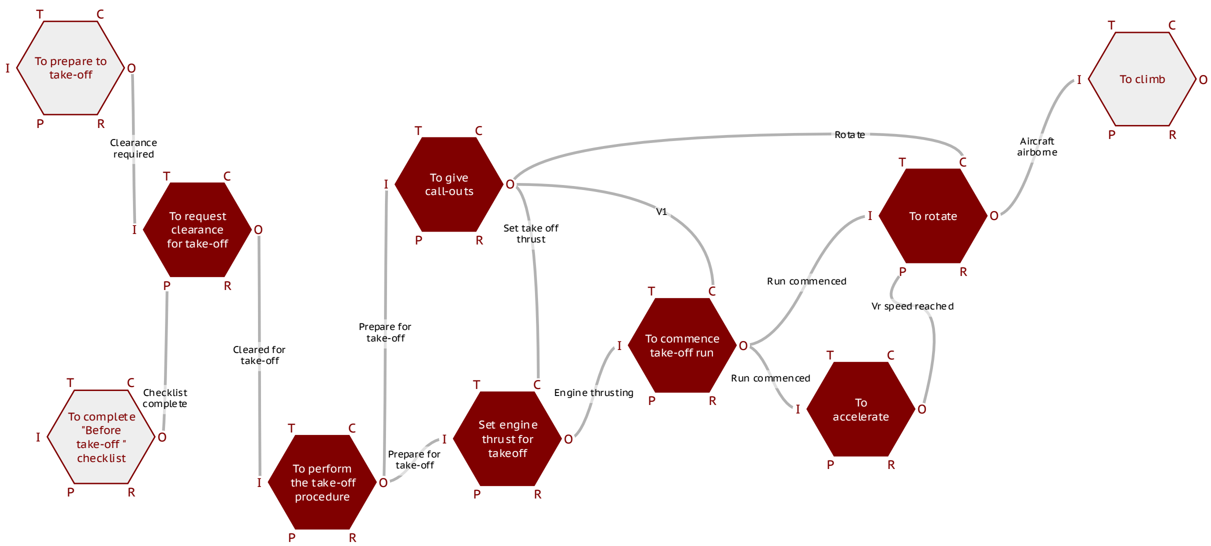

Figure 3 – Simple FRAM model of the functions needed for a "generic" take-off, and the couplings between them.

Appendix 2 – Examples of studies using FRAM in aviation

Area studied	Cases / systems studied	Instantiation types	Research types
Accident or incident	• American Airlines AAL965 • Alaska Airlines ASA261 • Comair flight 5191 • Norwegian Air NAX541 • Mid-air collision (GL1907 and N600XL) • Ground collision (SAS686 and D-IEVX)	Accidents	Qualitative, semiquantitative
Air Traffic Management	• Aircraft route change • Air Transport System • AUTOPACE project • ERASMUS project • MSAW system • Transfers between ACC and APC units • Ground collision (USA1493 and SKW569)	Accident, Normal operations	Qualitative, semiquantitative
Cockpit operation	• Landing process • Weather radar interactive process • Airliner approach and landing • Light sport aircraft take-off	Normal operations	Qualitative, semiquantitative
Maintenance	• Aircraft maintenance	Accident	Qualitative
Airline operations	• Operation Control system (OCC) • Ground handling services • Large aircraft flight operations	Normal operations	Qualitative

Table 4 – Studies using FRAM in aviation from 2006 to 2019, adapted from Tian and Caponecchia (2020)