Systems Engineering process resilience: assessing and improving project review process using FRAM

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***Abstract* – Research and development projects within military organisations are constantly subject to risks and uncertainties and their performance are key to deliver the organisational value. Failing to meet project goals and objectives is critical, therefore, projects must be able to cope with an environment of complexity and pressure. The Resilience Engineering perspective that things go wrong by the same reasons they go right is key to address R&D project environments, and the Functional Resonance Analysis Method (FRAM) fits the need to assess and improve systems engineering process resilience. In this paper, the focus of the analysis will be the project review process, key milestone to the development process and project success.**

***Key Words* – Systems Engineering, Resilience, Resilience engineering, FRAM.**

I. INTRODUCTION

Resilience engineering focuses on helping people to achieve success while coping with complexity under pressure [1]. Research and development projects within military organisations, as every project, are subject to risks and uncertainty. If Risk management is entirely associated with systems engineering and project management [2], project resilience is one of the trends and the emerging topics in the area [3]. This work aims to assess and improve project resilience in the context of the Instituto de Aeronáutica e Espaço (IAE) by looking at the project review process at typical SE milestones and, using Functional Resonance Analysis Method (FRAM), to identify sources of variability and propose ways to manage resilience and variability.

This article is divided into 6 sections. In section II, a brief introduction to Resilience, Variability and FRAM will set the scene for the case study, the project review process in IAE, which will be discussed in section III. Following sections will provide the application of every 5 steps of FRAM for modelling, assessing, and improving resilience management of the process. Finally, an overview of the work as done in the conclusion and some insights for future works.

II. RESILIENCE, VARIABILITY AND FRAM

A. Resilience and Resilience Engineering

Resilience and Resilience Engineering are described by Aven as two of the recent advances on the foundation of Risk Assessment and Risk Management and address issues with respect to the safety of systems [4]. Instead of looking to things that go wrong, as usually do traditional approaches to safety, Resilience and Resilience Engineering address things that go right. It emerges as a consequence of understanding that the things go right by the same reasons they go wrong and this happens because performance vary with time and as a conclusion, Resilience Engineering defines safety as "the ability to succeed under varying conditions" [5]. Resilience is supported upon four cornerstones, as seen on Fig. 1.

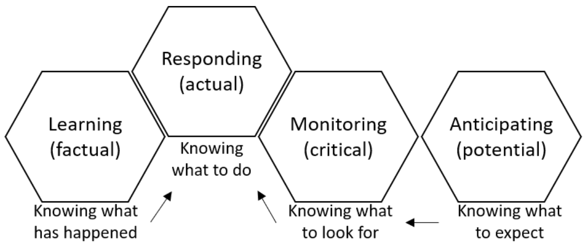

Fig. 1: The four cornerstones of resilience [5].

B. Functional Resonance Analysis Method – FRAM

The Functional Resonance Analysis Method (FRAM) was initially proposed by Erik Hollnagel in 2004, and has been developed in congruence with the principles of Resilience Engineering. It aims to describe everyday performance and model performance variability in complex dynamic socio-technical systems [6].

By defining a system as "a set of coupled or mutually dependent functions" [7], FRAM is more than a method to model processes, which are usually associated with simple linear thinking, establish cause-effect relationships that usually are associated with a timeline. FRAM models relationship between functions from a systemic perspective, which means properties may emerge from variability and resonate within the system.

Functions in FRAM are coupled to each other through six aspects: input (the which is processed through the function), time (which determines a temporal constraint), preconditions (which must be met for the function to be performed), resources (which are consumed during the performance), control (which determines control or monitoring conditions during the performance), and the output (which may be an entity or a state change). Fig. 2 shows how a function is represented when modelled with FRAM.

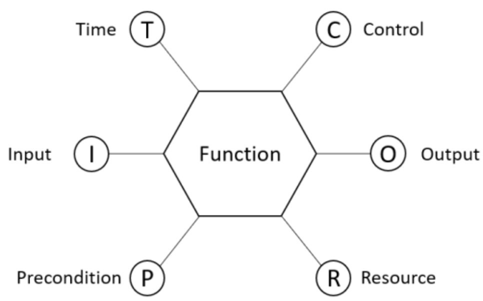

Fig. 2. A hexagon representing a function [7].

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FRAM is built upon four principles: "equivalence of failures and successes", which means that things go wrong by the same reason they go right; "approximate adjustments", which states that everyday performance always adjusted to match its conditions; "emergence", in the systemic sense, which many of the outcomes, predicted or not, must be described as emergent rather than resulted; and "resonance", through which relations and dependencies among functions are not cause-effect links, but "described as they develop in a specific situation" [7].

Hollnagel proposes four steps for using FRAM and one, which is necessary prior to the analysis, called "Step 0", which is to define the purpose of the analysis [7]. FRAM may be used either for event investigation (to look at what have happened) or for risk assessment (to predict what may happen in the future). Step 1 identifies the functions and describes how something is done through connecting the functions' aspects, then Step 2 will characterise potential and actual variability in FRAM. Then, Step 3 will aggregate variability by looking at specific instantiations of the model and, finally, Step 4 allows the user to propose ways to manage performance variability.

C. Evaluating the process performance variability

Hollnagel proposes in step 3 a method for the aggregation of variability as a result of the upstream-downstream couplings for the aspects of every function [7]. His method, however, was essentially qualitative. In 2010, Luigi Macchi [8] proposed an increment for Hollnagel's approach for evaluating the performance variability through an application of the FRAM giving integer scores for aspect's qualities. For every function, its upstream aspects are assessed with respect to its quality, then quality is related to how performance variability is either dumped or amplified. Table I relates, like Hollnagel's, temporal and precision quality of aspects, and Figure 3a and b relates quality of aspect to potential for increasing or decreasing variability. Scores corresponding to the potential for increasing are positive (+) and, for damping, are negative (-), and the values for high, medium, and low are respectively +/-3, +/-2 and +/-1. Then, the quality of the output of a function would be determined by the median of the quality of the aspects provided by functions upstream. Therefore, for functions with *n* aspects upstream, the quality of its output is given by (1).

$$q_o = median(q_{a_1}, q_{a_2}, \dots, q_{a_n}) \quad (1)$$

TABLE I. CHARACTERISATION OF FUNCTIONS OUTPUT [8]

		Temporal characteristics		
		Too early	***On time***	***Too late***
Precision	***Precise***	**A:** output to downstream functions is precise but too early	**B:** Output to downstream functions is precise with the right timing	**C:** Output to downstream functions is precise but delayed, reducing available time
	Appropriate	**D:** output to downstream functions is appropriate but too late	**E:** output do downstream functions is appropriate with the right timing	**F:** output to downstream functions is appropriate but delayed, reducing available time
	Imprecise	**G:** output to downstream functions is imprecise and too late	**H:** output do downstream functions is imprecise but correctly timed	**I:** output to downstream functions is imprecise as well as delayed, reducing available time

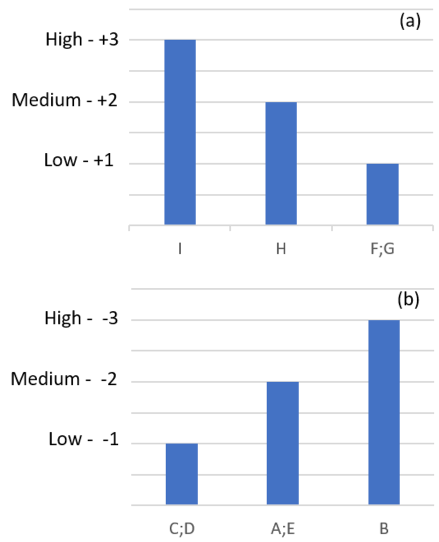

Fig. 3. Increasing (a) and damping (b) potential as a function of the aspect's quality, with their respective scores [8].

For this work, another factor considered was complexity of a function, as well as precision and timely aspects, but not simultaneously. Complexity will be a source of variability if operator is not well trained or used to the function they are supposed to perform. Scores are also given considering low, medium, or high potential for damping or increasing variability. Such assessment is done from the perspective and experience of the user of the framework. In this work, complexity scores will be explained with some rationale (as seen on Table IV).

III. CASE STUDY: SE PROJECT REVIEW IN IAE

A. Systems Engineering Process and Project Reviews at IAE

In order to fulfil its strategic mission:

> "to develop technological and scientific solutions to strengthen Brazilian Aerospace power through research, development, innovation […] in aeronautical, space and defense systems" [9]

The Instituto de Aeronáutica e Espaço, as an effort to standardise the organisational processes, developed its own Systems Engineering approach, aligned with several standards and good SE practices and the procedures for product lifecycle [10] and project lifecycle [11] at the Brazilian Air Force. The results are two internal standards for project lifecycle phases [12][13], and one for project review procedures [14]. For aeronautical and defence systems, the phases of development and their main project reviews are described in Table II.

TABLE II. PHASES AND PROJECT REVIEWS/MILESTONES FOR AERONAUTICAL AND DEFENCE SYSTEMS DEVELOPED IN IAE

Phase	***Phase description***	***Main project review / milestone***
0	Mission analysis	Mission Definition Review (MDR)
A	Feasibility	System Requirements Review (SRR)
B	Definition	Preliminary Design Review (PDR)
C	Development	Critical Design Review (CDR)
D	Qualification / Certification	Qualification Review (QR)

B. Project Review Process

Project reviews are milestones in which the project maturity, with respect to the correspondent phase, is assessed by an independent group of experts. Blanchard [15] and INCOSE [16] emphasize how important project reviews are to evaluate whether the project is heading towards its original goals and meeting the phase criteria or not. If the project meets the requirements as stated in the standards, or a subset of requirements stated in its Systems Engineering Management Plan as a result of a tailoring process, the project is considered approved to proceed to the next phase or milestone. If the project fails to meet all the requirements, it may either be approved, conditioned to the project team establishes a plan for meeting the requirements in time for the next milestone, or it is considered reproved and the review must be retaken.

The "Project Review Procedures" internal standard [14] was developed by the Systems Engineering Office (SEO) [17] and derived from some international standards and procedures, such as ABNT/ISO [18], ECSS [19] and NASA [20]. There are 3 main groups or actors involved with the process: the Project Review Team (PRT), which will be responsible for representing the whole project team and giving all the information necessary; the Review Committee (RC), which consists of invited and independent experts, who will be responsible for assessing the project and the evidences provided by the Project Review Team (PRT); and the Review Authority, who acts as a moderator and is responsible for process quality assurance and ensuring that Review Committee (RC) works independently and free of political pressure for either approving or reproving the project.

The Project Review process consists of 4 subprocesses:

1. *Prepare project review*: consists of assigning the Project Review Team (PRT), gathering the evidences of meeting the criteria for the selected milestone, inviting experts for the Review Committee (RC), communicating to the SEO the intention of conducting a review and planning the whole process (communications, meetings, etc.)
2. *Assess evidence*: to commence the process, PRT discloses the data pack with documents and evidence, which shall be assessed by the RC. Comments and questions are issued in a register, which will be replied by an assigned PRT member. This subprocess goes on until register is scheduled to be closed and consolidated by the PRT.
3. *Assess project*: After reviewing the documents in the data package, RC presents its initial conclusions at a Coordination Meeting, which is mandatory. From RC's considerations, they shall issue Review Item Discrepancies (RIDs), which are supposed to be fixed by the PRT or to be addressed by a fixing plan by the PRT. Answers to the RIDs are assessed by the RC, which will consider whether answers are adequate or not to fix the discrepancy.
4. *Close review process*: RC shall present its final conclusions after evaluating answers to the RIDs and approve if all milestone criteria were met, recommend approval under restrictions if one or more criteria were not met, but RID responses are considered adequate, or deny approval. Approval under restrictions need Portfolio manager's approval. After Review Authority consent, review process shall be evaluated by its participants and a final report is issued.

As an internal standard, it represents a description for the work as imagined. Its last appendix describes a process flow using Business Process Model Notation, designed using Bizagi® software. As already discussed in section II, this is a result of a straight linear thinking and likely not to describe the real work as done, but it is helpful when modelling for retrospective purposes.

IV. MODELLING THE WORK AS DONE

Before initiating Step 1, it is necessary to determine the purpose of the analysis. As stated in the introduction, this work aims to assess and find ways to improve the resilience in the Systems Engineering process by looking at the project review process. Therefore, the purpose is to predict what may happen in the future, but with a particularity: project reviews process are supposed to happen several times during a project lifecycle, so monitoring work actually "as done" will give further information.

FRAM modelling of the process was aided by the process flow at the project review standard [14] and by monitoring the Mission Definition Review (MDR) for the Project IFF Mode 4 NSM, which is currently under development by IAE [21]. The model was done using the FRAM Model Visualiser (FMV) [22].

All 4 subprocesses described in section III B were modelled individually from work-as-imagined (WAI) into work-as-done (WAD) and then collapsed into a high-level perspective, as seen in Fig. 4. Functions in green are all 4 subprocesses, whereas functions in purple and in red are background functions, such as Plan Project, Execute Project, Monitor and Control Project, Execute yearly activities (from organisational perspective), Manage Project, and Standardise project management processes. They are not a direct part of the main process, yet they are sources of variability. These functions and their outputs must be considered for the next steps.

Fig. 4: FRAM model of the high-level project review process

Given the aspects that emerged during the MDR process for the Project IFF Mode 4 NSM, subprocess "2. Assess evidence" raised a flag and, therefore, was taken into consideration for further analysis. The interaction between PRT and RC did not work as imagined, which considered a loop of comments and questions continuously being replied. Although the interaction happened, there was little feedback to the process, and few comments and questions were reassessed by RC. Fig. 5 gives further details on how work was imagined for the internal standard, and Fig. 6 shows the FRAM model for this subprocess, in which green functions are organisational considered in WAI model, yellow functions are human functions considered in WAI, red functions are human functions not considered in WAI and grey functions are background functions.

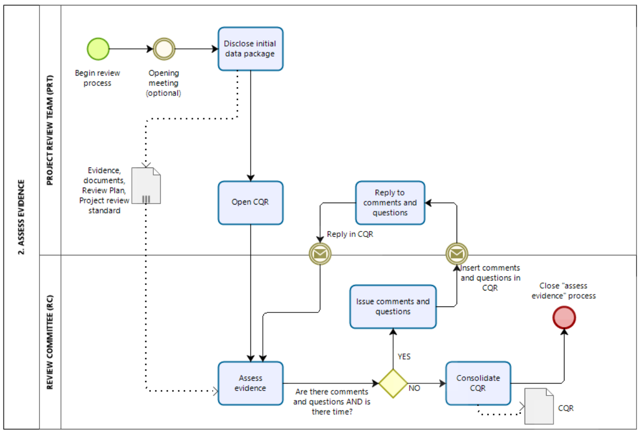

Fig. 5: Subprocess "2. Assess evidence" as imagined.

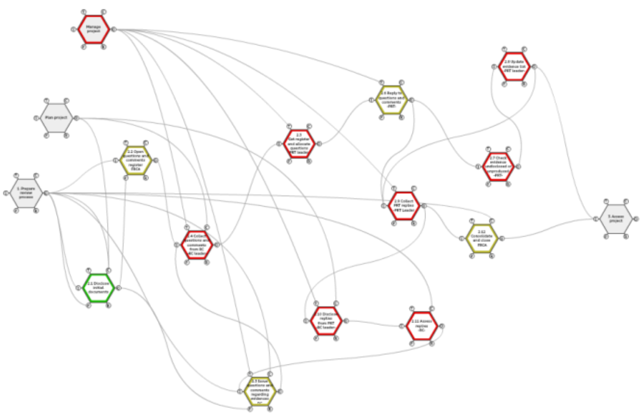

Fig. 6: FRAM model for subprocess "2. Assess evidence".

Functions from Fig. 6 that are relevant to our study, with their respective outputs, are described in Table III. The output flow goes downstream up to a feedback, in which replies are assessed by the RC and give them more information to interactively assess the evidence.

TABLE III. FUNCTIONS IN SUBPROCESS 2 AND ITS OUTPUTS

Nº	*Function*	*Output*
2.1	Disclose initial data package	Data package disclosed
2.3	Issue questions and comments about evidence	Comments and questions
2.4	Collect questions and comments from RC	CQR with questions and comments
2.5	Get CQR and assign questions to PRT	Questions and comments allocated
2.6	Reply questions and comments	Questions and comments replied
2.9	Collect PRT replies	CQR with replies
2.10	Disclose replies to RC	CQR with replies disclosed
2.11	Assess replies	Replies assessed
2.12	Consolidate and close CQR	CQR consolidated

FEEDBACK

Here is a brief description of each function:

- 2.1 – Disclose initial data package: as the review process begin, the RC shall receive the data package to assess the evidence. Review plan helps to set a deadline for disclosing, but this may vary. RC members should also sign a confidentiality agreement if the project data access is restricted, which is the case for several of the projects in IAE.
- 2.3 – Issue comments and questions about evidence: RC members, experts invited due to their experience with other development projects, shall assess the evidence. Usually, there is a need for clarification, therefore comments and questions are issued. The quality of this process depends on the RC members expertise, which is defined in subprocess 1. Prepare Review.
- 2.4 – Collect questions and comments from RC – Review Committee leader shall gather every RC members' comments and questions and send them to the Project Review Team leader.
- 2.5 – Get CQR and assign questions to PRT: PRT leader shall assign questions and comments to be replied by the most fit project team member, with respect to the matter discussed.
- 2.6 – Reply questions and comments: PRT member assigned by the PRT leader shall reply to their comments and questions and send them back to the PRT leader.
- 2.9 – Collect PRT replies: as PRT members reply to their assigned questions and comments, PRT leader shall collect them to send a new version of the CQR to RC leader.
- 2.10 – Disclose replies to RC: RC leader discloses the latest CQR version to the other RC members.
- 2.11 – Assess replies: RC members assess replies given by PRT members and shall consider if further information is required and, so, issuing new comments or questions.
- 2.12 – Consolidate and close CQR: Review Plan defines, in its schedule, a deadline for the subprocess 2, whether assessment had been successfully done or not. After the deadline, review process proceeds to the next step, which is to assess the project at the Coordination Meeting.

Background functions play a major role as a source of variability with respect to the quality of their outputs and must be considered, either from a precision/timely (P/T) perspective or from a complexity (Cp) perspective. Table IV gives further detail on background functions and quality of their outputs and Table V relates background functions and functions of subprocess 2 with respect to their aspects (I – input, P – precondition, R – resource, T – time, and C – control). Scores are given according with their potential for increasing or damping potential in Fig. 3.

V. IMPROVING THE PROCESS RESILIENCE

A. Aggregating variability

After steps 1 and 2, step 3 will aggregate variability and step 4 will propose ways to manage variability. Once it was possible to monitor one round during the Project "IFF Modo 4 NSM – Fase 2" Mission Definition Review, one of the scenarios for aggregating variability will be the work-as-done. Other four scenario will be considered, using two variables: Project Manager expertise, which impacts output of background function 0.1, and RC members expertise, which impacts output B for background function 1. Both variables will have a "best-case" and a "worst-case" scenario. For instantiation where both are "best-case" scenario, a "worst-case" scenario will be added for level of access, adding more complexity to the process through output of background function 0.2. Table VI gives all five instantiations and Table VII gives relative scores with respect to potential for damping or amplifying variability for each scenario.

Using the variability aggregation method as in section II, B, scores were propagated through the functions and the results can be seen in Fig. 7

TABLE IV. BACKGROUND FUNCTIONS AND THEIR OUTPUTS

Function	***Output***	***Description***
0.1 Manage project	Pressure upon review schedule (Cp)	Determined by Project Manager's expertise and approach to the team. A healthy pressure may lightly damp variability (-1), whereas lack of expertise or excessive pressure may amplify variability (+2 or +3).
1. Prepare review	A. Project Review Plan (Cp)	Project Review Plan has little effect over the process, although it establishes a schedule and enlightens stakeholders with respect to their roles and responsibilities, which may be regarded as a low damp factor (-1).
	B. RC members expertise (Cp)	Depending on the expertise of the invited members of RC, good knowledge of the industry or with past similar projects damp variability (-1 or -2), whereas lack of expertise or knowledge of the subject of the review, or even the review process itself, may be a factor that amplifies variability (+1 or +2).
	C. Initial list f evidence (P/T)	Usually delivered on time (D, -1). If project manager is unexperienced or do not pay attention to producing the evidence prior to the milestone, then output quality may be imprecise (H, +2).
	D. Signed confidentiality agreements (P/T)	Usually, delivered too late. There is no record of inappropriate output, which would mean RC member would not take part in the process. (F, +1).
	E. Data package ready for distribution (P/T)	Usually, delivered on time, but not usually precise, because typically there is a need to add new information to the initial data package (E, -1). Level of access may couple and delay the distribution (F, +1).
0.2 Plan project	Documentation level of access (Cp)	R&D projects at IAE usually are classified and this adds complexity to the process, especially regarding data transmission. Medium or high potential to amplify variability.

TABLE V. RELATIONSHIP BETWEEN BACKGROUND FUNCTIONS AND FUNCTIONS AT SUBPROCESS "2. ASSESS EVIDENCE"

	2.1	2.3	2.4	2.5	2.6	2.9	2.10	2.11	2.12
0.1		T	T	T	T	T	T		
0.2	C	C	C				C		
1.A	C	C							T
1.B		C						C	
1.C		I							
1.D	P								
1.E	I								

TABLE VI. INSTANTIATION SCENARIOS

Scenarios	***PM expertise & attitude***		***RC expertise***		***Level of access***
	BEST	WORST	BEST	WORST	
WAD	WORK AS DONE				
Scenario 1		X		X	REGULAR
Scenario 2	X		X		HIGH
Scenario 3	X			X	REGULAR
Scenario 4		X	X		REGULAR

TABLE VII. SCORES FOR THE INSTANTIATION SCENARIOS

Function / output		***Scenario***				
		WAD	1	2	3	4
0.1	Schedule pressure	+2	+3	-1	-1	+3
1.A	Review plan	-1	-1	-1	-1	-1
1.B	RC expertise	-1	+2	-1	+2	-2
1.C	Initial data list of evidence	+1	+2	-1	-1	+2
1.D	Confidentiality agreements	+1	+1	+1	+1	+1
1.E	Data pack ready	+1	+1	+1	+1	+1
0.2	Level of access	+2	+2	+3	+2	+2

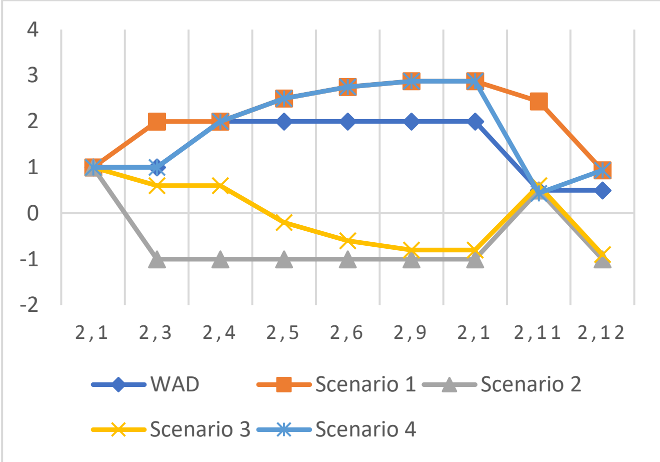

Fig. 7: Aggregation of variability and propagation through the process.

B. Managing variability

From the results in Fig. 7, 3 main findings may be drawn in the Step 4 of FRAM. Firstly, the results from the WAD scenario reflect how the process was performed. As stated in section IV, there was little interaction after comments and questions were replied by the PRT. This was partially due to the comments being issued with precision, but too late (F, +1), which is exactly the model quality output for function 2.3. Functions downstream were performed out of time or not even performed, which is in accordance with the results given by the model.

Secondly, Comments and Questions Register (CQR) consolidation is an event with a clear deadline, given by the Review plan, and is a pre-requisite to execute the Coordination Meeting, a mandatory event within the process. Output quality of function 2.12 drops in almost every scenario (except in scenario 4), which was expected. Output quality +1 may indicate issues with precision, which can be translated into information quality. This is the case for both scenarios in which RC expertise is at worst-case scenario, and, hence, justified.

Finally, the Project Manager attitude and expertise play a major role in the variability aggregation. A skilled, well-trained project manager, with a good attitude, will cope with adjustments necessary after planning is done and help their team towards meeting the process objectives with more ease. This impacts other functions, mostly related to the Project Management processes, such as risk management and leadership, which will keep team motivation and readiness levels high. If, on the other hand, the project manager is unexperienced, lack of attitude or puts too much pressure on their team, variability will be amplified, as seen in scenarios 1 and 4. This last conclusion could have been found in other sources that discuss the role of the project manager and good project management practices [23], [24], [25], but it shows that the model gives results that are coherent with the main bodies of knowledge.

In order to close step 4 and the whole FRAM analysis, there are two actions which are suggested to manage variability. Firstly, to provide better training and environment for Project Managers. Well trained PM can manage their own team and to oversee the whole process from both project management and systems engineering, which will help them to increase the whole Systems Engineering process resilience. Also, good PMs will allow room for small adjustments to the original plans, should things work differently than expected (which they do). The second action, which is coupled to the first, is to give clearer instructions to participants within the project review process. This will help participants to clearly understand their roles and responsibilities, especially those external experts invited to the Review Committee, who may not be familiar with the whole review process. Resilience principles, however, must be considered: there must be room for small adjustments whenever they arise.

VI. CONCLUSION

After going through the 4 steps of FRAM, plus its Step 0, the Project Review Process now may have its resilience improved by the findings of the last step, such as investing in Project Management qualification and providing an environment where projects may adapt within the circumstances of its execution, therefore reaching the work's objectives as stated in the Introduction. FRAM, although imagined to model social-technical problems, proved to be fit to model an organisational problem and provided interesting insights that are coherent with good practices.

For future works, it would be interesting to expand the scope of the analysis and assess relationship between Systems Engineering and Project Management processes, which are closely related [26]. In an organisation such as IAE, research and development projects are its day-to-day operations, are subject to variability and may have its resilience improved with the help of FRAM.

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