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Study of the Functional Resonance Analysis Method (FRAM)
Applied to a Commercial Aviation Incident

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Abstract

It is considered that nowadays human factors are accountable for about 80% of aviation incidents and accidents. To study human factors in these occurrences, ICAO Circular 240-AN/144 outlines a method based on the SHELL and Reason's models. Human factors can be identified using a taxonomy based on SHELL, presented in the same Circular. A different taxonomy based on Reason's model, called HFACS, was later proposed by the US Department of Defense. Such method is heavily based on inductive reasoning, including a great amount of subjectivity from the investigator. The study evaluates the utility of the recently introduced Functional Resonance Analysis Method (FRAM) in supporting the investigator in an accident or incident analysis. The incident examined in the study occurred on 12 December 2015 at Barcelona Airport and involved a Boeing 737-800 that was lifted by the airbridge while disembarking the passengers. The incident is first analysed using SHELL, the HFACS taxonomy and Reason's model. Next, the incident is analysed using FRAM and the relevant human factors are identified using HFACS again. The two methods are then compared in terms of results and principles. In conclusion, FRAM has proved to be a valuable tool in supporting the safety analysis and in reducing its subjectivity, particularly by offering a scheme to develop a specific model of the considered system in its everyday functioning. In the study, the main weakness of FRAM, namely the proposal of mitigation measures, is compensated for by incorporating the HFACS taxonomy in the last step of the analysis.

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Last, but definitely not least, I would like to acknowledge the help provided by Emanuele Sbrozi. His generosity in explaining and showing me the functioning of airbridges and the relative procedures made my visit at Malpensa Airport greatly useful and interesting.

Disclaimer

In this study a commercial aviation incident is analysed by means of scientific methods leading to useful Safety Recommendations. Nevertheless, the goal is not to reinvestigate the incident, since the author is not privy to all the facts and findings of the event. This study does not intend to substitute in any case the official incident investigation; instead, it uses the causal factors determined by the Spanish CAA, CIAIAC.

It is also important to note that the study is presented for illustrative purposes only. While the author has attempted to maintain the spirit and accuracy of the CIAIAC report by citing specific findings and analyses, in the interest of compactness, the author has only presented those details necessary to support the causes and contributing factors associated with the incident.

The official report regarding this occurrence can be found at: https://www.fomento.gob.es/recursos_mfom/2015_035_in_0.pdf

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List of Symbols and Abbreviations

CAA .... Civil Aviation Authority

CIAIAC .... Comisión de Investigación de Accidentes e Incidentes de Aviación Civil

CPC .... Common Performance Condition

EB .... Effective Barrier

FRAM .... Functional Resonance Analysis Method

HFACS .... Human Factors Analysis and Classification System

HMI .... Human-Machine Interface

ICAO .... International Civil Aviation Organization

M .... Human Function

O .... Organisational Function

T .... Technical Function

1. Introduction

Deloitte has been studying the subject of aviation incidents and accidents for years.

At the beginnings of aviation, technical failures were the main cause of accidents and incidents but, with the advance of technology, human factors started to prevail as the cause of these occurrences. Estimates in the literature point out that in recent times human factors can be accounted for the main or concurring cause in 70-80% of all aviation incidents and accidents. The graph in Figure 1.1 shows this trend.

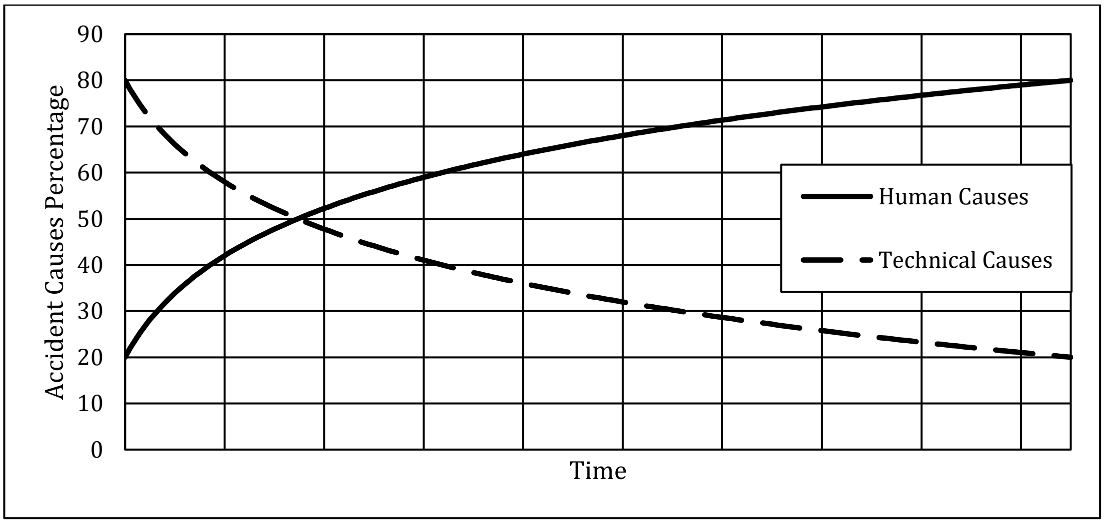

Figure 1.1 Hypothesized percentage of accident causes as a function of time

Given this data, the attention in safety analyses has progressively shifted to human factors. An accident or incident investigation conducted within the frame of ICAO Annex 13 is affected by a certain amount of subjectivity. Regarding human factors, the ICAO Circular 240-AN/144 outlines a methodology using Reason's model and the SHELL model, including a taxonomy made up of about 450 human factors. According to the Circular, the investigation of human factors contemplates both deductive and inductive reasoning. Because most human factors conditions are hardly measurable inductive reasoning prevails, so the analysis is affected by a great dose of speculation and subjectivity from the safety analyst.

In principle, subjectivity is not a bad thing but depending on the competence and discretion of the investigator it could produce negative outcomes. For example, the investigator could have conflicting interests, preventing the actual causes leading to the analysed occurrence to emerge. This would produce mitigations that obviously do not address the root causes of the considered incident or accident and would be useless to prevent similar future occurrences.

To reduce the subjectivity and help the safety analyst in the task of identifying relevant human factors, Deloitte has developed a neural network application, called ATHENA. This programme is able to read incidents and accidents reports, the “findings” and “event analysis” sections, provided that the sentences are formatted so that each conveys only one piece of information. The application produces a classification of the sentences based on the SHELL human factors analysis method. So far, about 20 incidents and accidents have been analysed with the aid of this neural network with a success rate in identifying the correct SHELL component or interface of about 65%.

To improve the taxonomy based on the SHELL model proposed by ICAO, the Human Factors Analysis and Classification System (HFACS) was introduced. HFACS is based on Reason’s model and provides about 150 human factors related to the aviation field. HFACS also provides a nanocode and a description for every human factor considered. Once the HFACS nanocodes relevant to an accident or an incident are identified, the issuing of mitigation measures is easier because this process is guided by the descriptions provided. These are generally regarded as appropriate because they were prepared within a public body, the US Department of Defense, that has great interest in preventing incidents and accidents. Ultimately, the characterisation of human factors provided by HFACS diminishes the subjectivity of the last part of incidents and accidents analyses, namely the issuing of mitigations and safety recommendations.

However, induction – and subjectivity – are still largely present in the first phases of the investigation: the identification of the human factors.

The aim of this study is to examine if – and how – the Functional Resonance Analysis Method (FRAM) could be an effective tool to help the safety analyst in the investigation of accidents and incidents, within the frame provided by ICAO Annex 13, possibly reducing the subjectivity of the analysis. FRAM is a recent systemic tool that provides a scientific-mathematical framework to decompose a system into the functions that guarantee its everyday operativity.

The development of the study is centred on the incident occurred at Barcelona Airport on 12 December 2015 involving a Boeing 737-800 aircraft, registration number EI-DLR, operated by Ryanair.

First, a description of the incident is provided. Then the incident is analysed by means of the SHELL-HFACS method. The analysis, conducted with an established method within the aviation industry, is necessary to highlight the limitations of this method and to examine the potential utility of FRAM. Afterwards, the incident is analysed with FRAM and the results are compared with the ones obtained by the SHELL-HFACS analysis. Finally, the utility of FRAM in accidents and incidents analyses is assessed.

2. Description of the Incident

On 12 December 2015, the aircraft operating flight FR6399 from Seville to Barcelona was parked at position 101 at Barcelona Airport, disembarking the passengers through the airbridge. During the disembarking, after approximately 90 passengers had left the aircraft, at around 20:30 UTC (21:30 local time), a flight attendant noticed the unusual attitude of the aircraft nose. The flight crew, completing the checklist at that time, were promptly notified.

The crew confirmed that the aircraft was lifted by the airbridge connected to door L1, as shown in Figure 2.1. The passengers that were still on board were instructed to sit down and fasten their seat belts.

Figure 2.1 Attitude of the aircraft being lifted by the airbridge (CIAIAC, 2016)

A few seconds later, door L1 collapsed and the nose of the aircraft fell from an estimated height of 2 m and hit its nose gear.

Figure 2.2 shows the airbridge and the aircraft after the collapse of the door.

Figure 2.2 Aircraft and airbridge after the collapse of the door (La Vanguardia, 2015)

At the same time, while the airbridge was lifting uncontrollably, the audible warning in its cabin started. Upon arriving near airbridge 101, the ramp agent witnessed the lifting and subsequent fall of the aircraft. He disconnected the airbridge and manually deactivated the autolevelling system.

At the time of the event, approximately 90 passengers had disembarked through the airbridge; the remaining ones still inside the aircraft were disembarked through the rear door.

Upon disembarking, a passenger reported knee injury and another showed anxiety. The airport requested medical assistance and the ambulance arrived at the aircraft in two minutes. It offered medical assistance to two passengers with discomfort or injuries.

It is considered that while the aircraft remained at the same height of the airbridge, passengers disembarking were not in danger. However, the collapse of the front door could have caused injuries to passengers. These would have been more severe had the cabin crew not requested the passengers still aboard to sit down and fasten their seatbelts.

Door L1 of the aircraft broke and collapsed, while subsequent examinations showed that the landing gear and tail cone were not damaged during the event. The airbridge was severely damaged as well.

The damages suffered by the aircraft door are shown in Figure 2.3.

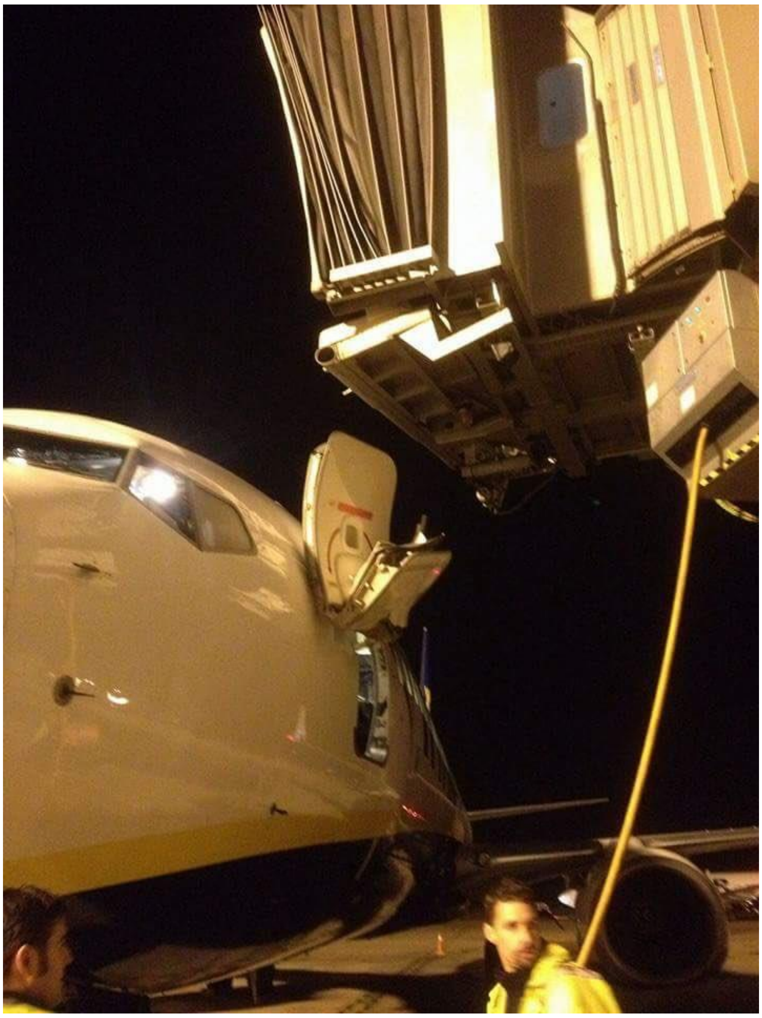

Figure 2.3 Damage suffered by the aircraft door (Sevilla Vuela, 2015)

The affected airbridge had a long service life, being installed in 1991. It underwent major renovation in June 2015. Such renovation included, among other things, the development of new software to control the movements of the airbridge.

It is considered that the uncontrolled lifting of the airbridge was caused by the combination of the failure of the electrovalve of the hydraulic elevation circuit and the modification of the interval for the activation of the pump of this circuit of the self-levelling system, that occurred during the renovation of the finger a few months before.

Two safety recommendations were issued to Barcelona Airport and to the joint venture performing the airbridges renovation at said airport.

3. Study of the Incident with SHELL and HFACS

3.1. Introduction to SHELL

The SHELL model was developed by Professor Edwards in 1972 and later modified by Hawkins. It provides a systematic approach to an incident or accident investigation facilitating data collection and analysis.

The centre of the model is the human component (L) that interacts with four other components, namely software (S), hardware (H), environment (E) and liveware (L). Each one of them is a separate field of study relating human factors. Every block is portrayed with irregular edges and as the human component does not work autonomously such edges need to be carefully matched to avoid potential stress and breakdown. A depiction of the SHELL model is shown in Figure 3.1.

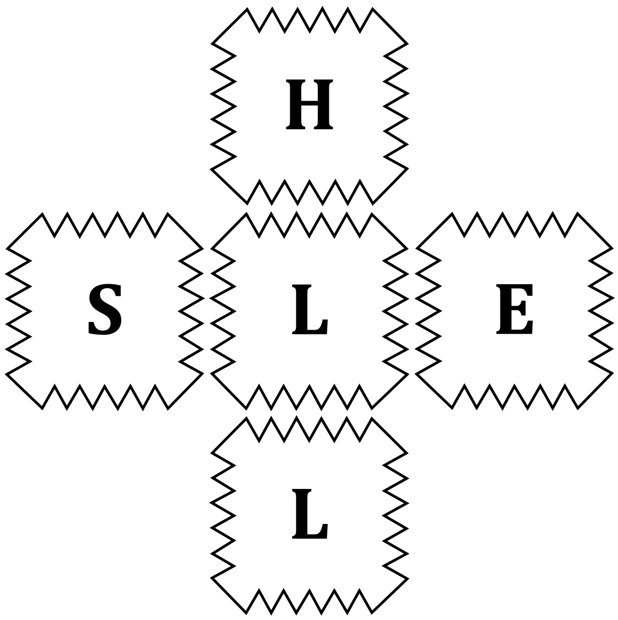

Figure 3.1 Depiction of the SHELL model

Human factors investigation must inquire into mismatches that could be the cause of the negative occurrence being analysed. The data gathered in the investigation is fundamental to allow a deep comprehension of the SHELL components so that the status of each of them and of the interfaces of the model can be assessed.

The components and their interfaces can be described as follows:

1. **Liveware (individual)**: the centrepiece of the model, its description is done through physical, physiological, psychological and psychosocial factors;
2. **Liveware – Liveware** interface represents the interaction between the people in the workplace and the individual, such as staff-management relationships;
3. **Liveware – Hardware** interface represents the interaction between humans and machines;
4. **Liveware –Software** interface represents the interaction between the individual and any kind of support system in the workplace, including written information and computer software;
5. **Liveware – Environment** interface represents the interaction between the individual and both the internal environment, meaning the work area, and the external environment, including the area outside the work area and any economic or political restraints.

Once the data on the incident and the human factors involved has been collected it needs to be analysed. Conclusions are drawn either through deductive or inductive reasoning. The former is best suited for the few human factors that can be easily measured such as hearing and drug or alcohol impairment. Conclusions based on deduction are indisputable and can be easily presented. On the other hand, inductive reasoning is the most common way of drawing conclusions in human factors analyses as most human factors themselves are not measurable, such as distraction or complacency. Induction produces results that are less precise than the ones obtained through deduction and thus they can be easily challenged. Their strength depends on the reasoning process used by the investigator and the quantity and quality of the evidence collected. Based on such evidence, induction comprises a good degree of speculation from the investigator in determining the probability and likelihood of the existence and influence of a human factor condition.

A multi-step approach made up of three tests is advised to guide the investigator through this task:

1. **Test for existence**: this step focuses on determining all the human factors to consider, the ones that need thorough examination and on comparing the conditions of the event with established knowledge in the field of human factors

to evaluate the probability that a human factor condition existed at the time of the event;

2. **Test for influence**: this step focuses on gathering information on the effects produced by the conditions examined in step 1, on comparing the course of action of the people involved in the event with the applicable established knowledge and on assessing the probability that the human factors conditions had any influence on the performance of the people involved and on the event as a whole;
3. **Test for validity**: upon completion of steps 1 and 2 analysts will have information that allow probabilistic conclusions that are drawn based on their knowledge of the subject and available evidence, having considered all likely factors at any decision level, as is done with Reason's model.

In addition to this process, several checklists are available to aid the analyst in the assessment of human factors. One of them proposes a human factors taxonomy with approximately 450 elements.

3.2. Introduction to Reason's Model and HFACS

The Reason model, also known as the organisational incident model, was developed by James Reason and represents the aviation industry as a complex system. Decision-makers are one of the components of the system: they set the goals of the organisation and manage its resources to achieve the best trade-off between safety and timely, cost-effective performance. Line management is another component of the system, making the workforce execute the measures taken by the decision-makers. For the front-line operators to act in an effective way some preconditions must be met, and defences must be put in place to prevent incidents and accidents. As technology advances and systems become more complex accidents are rarely caused by the front-line operators only and can be traced back to the interactions of flaws and failures lying within the system.

Reason recognises four sequential failure domains in the system:

1. Organizational influences;
2. Unsafe supervision;
3. Preconditions for unsafe acts;
4. Unsafe acts.

From this decomposition Reason's model has a strong focus on the organisational aspect of the aviation industry and the causes of an accident or incident can be positively identified inside the four domains.

The system can be further described as a stack of four swiss cheese slices with gaps in-between. Each slice represents the defences in every domain, while the holes are the weaknesses of the system, failures and flaws, varying in size and position. If the holes align, then a "trajectory of accident opportunity" generates and a hazard can pass through. If the defences work it leads to an incident, if they do not work it leads to an accident.

Failures are classified into active and latent failures. The former meaning an error or violation that immediately produces a negative effect; the latter meaning decisions or actions made at higher levels than the workforce, or human conditions present at any level that show their effect later in time.

Such failures, portrayed as holes in the safety barriers, can be classified by means of the Human Factors Analysis and Classification System (HFACS). This system was developed by Wiegmann and Shappel to deal with increasing problems relating with human performance in the US Navy. HFACS retains the level distinction made by Reason and further breaks down each level into causal categories that allow the identification of the latent and active failures. HFACS provides a taxonomy made up of about 150 entries of human factors in aviation. Identifying HFACS nanocodes relating to an incident facilitates issuing mitigation measures and provides a common ground to analyse an incident or accident from the human factors perspective. Figure 3.2 shows the breakdown of the four failure domains into the causal categories and the relative series number of the pertaining nanocodes.

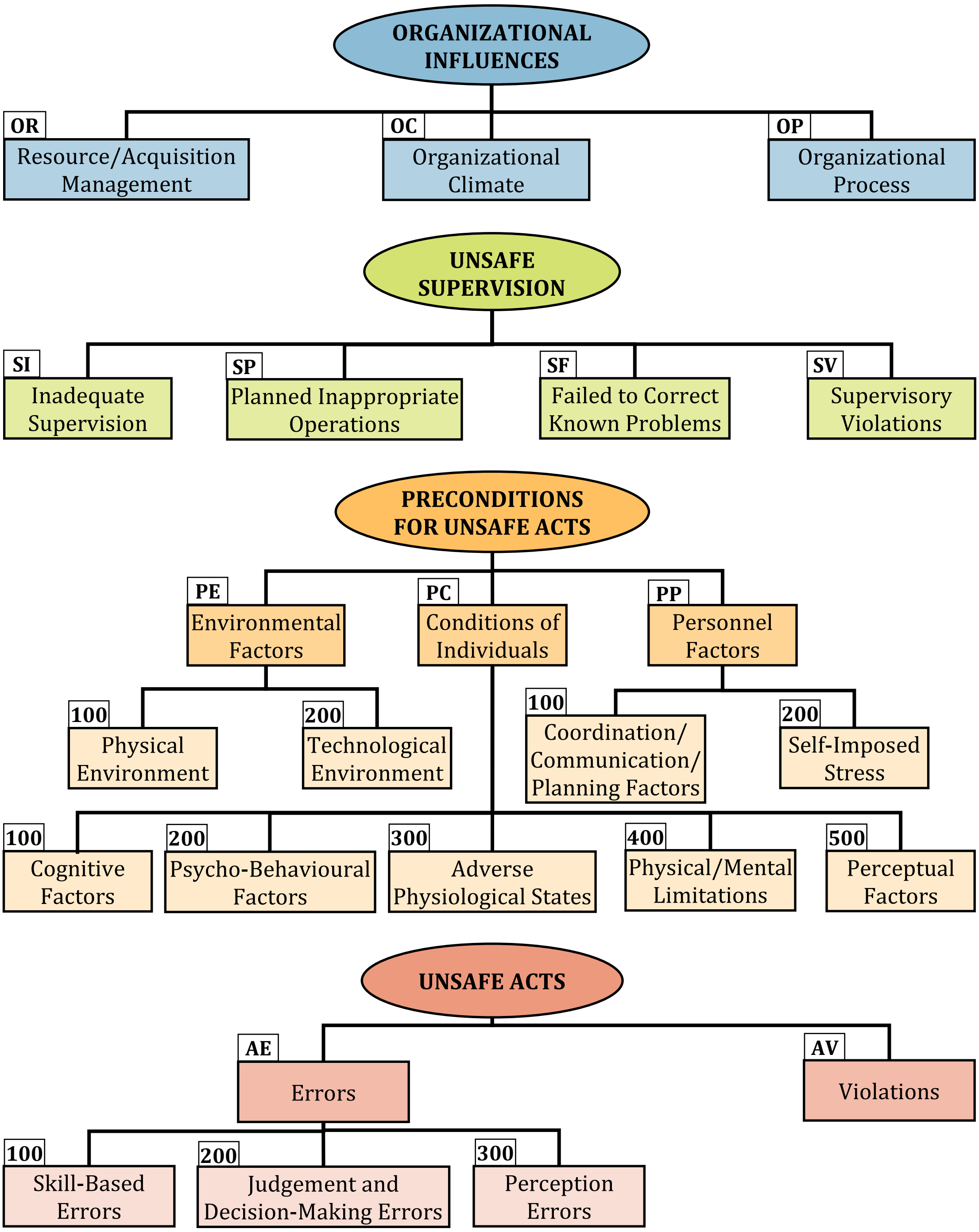

Figure 3.2 HFACS breakdown of failure domains

3.3. SHELL and HFACS Analysis

3.3.1. SHELL human factors identification

The analysis starts with the identification of SHELL human factors as they are more numerous and therefore more approachable than HFACS entries.

The identification of the human factors involved in the event is based on the incident report drafted by the Spanish CAA. The findings of the investigation are isolated so that each conveys one piece of information to make the human factors identification easier. The sentences obtained are:

F1. All flight crew members had their permits and medical certificates valid and in force.

F2. The uncontrolled lifting of the airbridge, up to its maximum operational height, took place during the disembarking of the passengers, when 90 passengers and relative baggage had already been disembarked.

F3. An audible alarm notifying the airbridge failure sounded and was heard by the ramp agent that was in the airbridge cabin.

F4. The flight assistant noticed the behaviour of the aircraft nose and halted the disembarkation of the passengers.

F5. The crew immediately started the emergency procedure.

F5.1. Passengers were requested to sit down, fasten their seatbelts and to assume brace position.

F6. The left front door collapsed, and the front airframe of the aircraft fell over the nose gear from an approximate height of 2 m.

F7. The inspection and functional tests of the airbridge revealed the failure of an electrovalve of the elevation hydraulic circuit of the airbridge autolevelling system.

F8. The renovation of the airbridge, carried out a few months before, included a large increase of the interval of sampling of the position control system (controlled via software).

F9. The incident was caused by the concurrent electrovalve failure and delayed action interval of the position control system of the autolevelling system.

F10. No risk assessment to determine failure modes of modified airbridges had been performed by the companies renovating the airbridges.

Every sentence is examined to verify that it conveys meaning regarding the presence of a human factor condition in the development of the incident. Out of all of them, sentences F1, F2, F6 and F9 are discarded as they do not relate to human factors or their meaning is better expressed by other sentences. Focusing on the remaining ones, it is necessary to identify the interface or the component of the SHELL model they are linked to, as shown in Table 3.1.

Table 3.1 SHELL interfaces and components identification

Software	**Hardware**	**Environment**	**Liveware People**	**Liveware Organisation**
F8. The renovation of the airbridge, carried out a few months before, included a large increase of the interval of sampling of the position control system (controlled via software).	**F3.** An audible alarm notifying the airbridge failure sounded and was heard by the ramp agent that was in the airbridge cabin.		**F4.** The flight assistant noticed the behaviour of the aircraft nose and halted the disembarkation of the passengers.	
F10. No risk assessment to determine failure modes of modified airbridges had been performed by the companies renovating the airbridges.	**F7.** The inspection and functional tests of the airbridge revealed the failure of an electrovalve of the elevation hydraulic circuit of the airbridge autolevelling system.		**F5.** The crew immediately started the emergency procedure. **F5.1.** Passengers were requested to sit down, fasten their seatbelts and to assume brace position.	

Based on this classification, the human factors relating to every sentence is determined using Checklist B of the ICAO Circular 240-AN/144. This checklist presents a list of possible human factors classified into the pertaining interfaces and components of the SHELL model. The selected human factors are presented in Table 3.2. The human factors identified as having a positive effect on the course of the events are marked as effective barrier, [EB].

Table 3.2 SHELL Human Factors identification

Finding	SHELL Human Factor
F3	Hardware – Equipment – Workspace – Alerting and warnings [EB]
F4	Liveware – Psychological Factors – Attention – Vigilance [EB]
	Liveware – Psychological Factors – Perception – Reaction Time – Reaction Time [EB]
F5 **F5.1**	Liveware – Psychological Factors – Training – Emergency Procedure [EB]
F7	Hardware – Equipment Failure
F8	Software – Computers – Computer Software
F10	Software – Written Information – Standard Operating Procedures

The proceeding in this paragraph so far is comparable to performing step one of the multi-step process advised by the SHELL method, namely the test for existence. Regarding the next step, the test for influence, it can be argued that it is likely that all the human factors found had an influence on the people involved in the incident and on the developing of the incident itself.

3.3.2. HFACS nanocodes and Reason's model of the incident

The HFACS nanocodes relevant to the incident are obtained starting from the SHELL human factors presented in paragraph 3.3.1. The HFACS nanocodes are identified using the SHELL–HFACS matching tool developed internally by Deloitte. Table 3.3 shows the HFACS nanocodes applicable to the incident being analysed, the human factors identified as barriers are marked as [EB].

Table 3.3 HFACS nanocodes identification

Finding	SHELL Human Factor	HFACS Human Factor	
		Code	**Name**
F3	Hardware – Equipment – Workspace – Alerting and warnings [EB]	PE202	Instrumentation and Sensory Feedback System [EB]
F4	Liveware – Psychological Factors – Attention – Vigilance [EB]	PC101	Inattention [EB]
	Liveware – Psychological Factors – Perception – Reaction Time – Reaction Time [EB]	AE301	Error Due to Misperception [EB]
F5 **F5.1**	Liveware – Psychological Factors – Training – Emergency Procedure [EB]	OP004	Organizational Training Issues/Programs [EB]
		PC405	Technical/Procedural Knowledge [EB]
F7	Hardware – Equipment Failure	PE205	Automation
		OR002	Airfield Resources
F8	Software – Computers – Computer Software	PE205	Automation
F10	Software – Written Information – Standard Operating Procedures	OP003	Procedural Guidance/Publications

Table 3.4 shows the HFACS nanocodes divided into the four levels of Reason's Model; once again, nanocodes pointing at barriers are marked with [EB].

Table 3.4 HFACS nanocodes divided into failure domains

Unsafe Acts	Preconditions for Unsafe Acts	Unsafe Supervision	Organisational Influences
AE301 Error Due to Misperception [EB]	PE202 Instrumentation and Sensory Feedback Systems [EB]		OR002 Airfield Resources
	PC101 Inattention [EB]		OP004 Organizational Training Issues/Programs [EB]
	PC405 Technical/ Procedural Knowledge [EB]		OP003 Procedural Guidance/Publications
	PE205 Automation		

From the analysis, the HFACS nanocodes that can be used to propose mitigations to prevent future incidents are: PE205 Automation, OR002 Airfield Resources and OP003 Procedural Guidance/Publications. On the other hand, the HFACS nanocodes that represented effective barriers at the time of the incident can be obtained denying the description of nanocodes AE301 Error Due to Misperception, PE202 Instrumentation and Sensory Feedback Systems, PC101 Inattention, PC405 Technical/Procedural Knowledge and OP004 Organizational Training Issues/Programs.

The Reason model of the incident is developed considering both failures and effective barriers within the system. In this case, flaws and failures are localized in the airport environment while effective barriers are found in the airline.

Figure 3.3 shows a graphic representation of the Reason model of the incident.

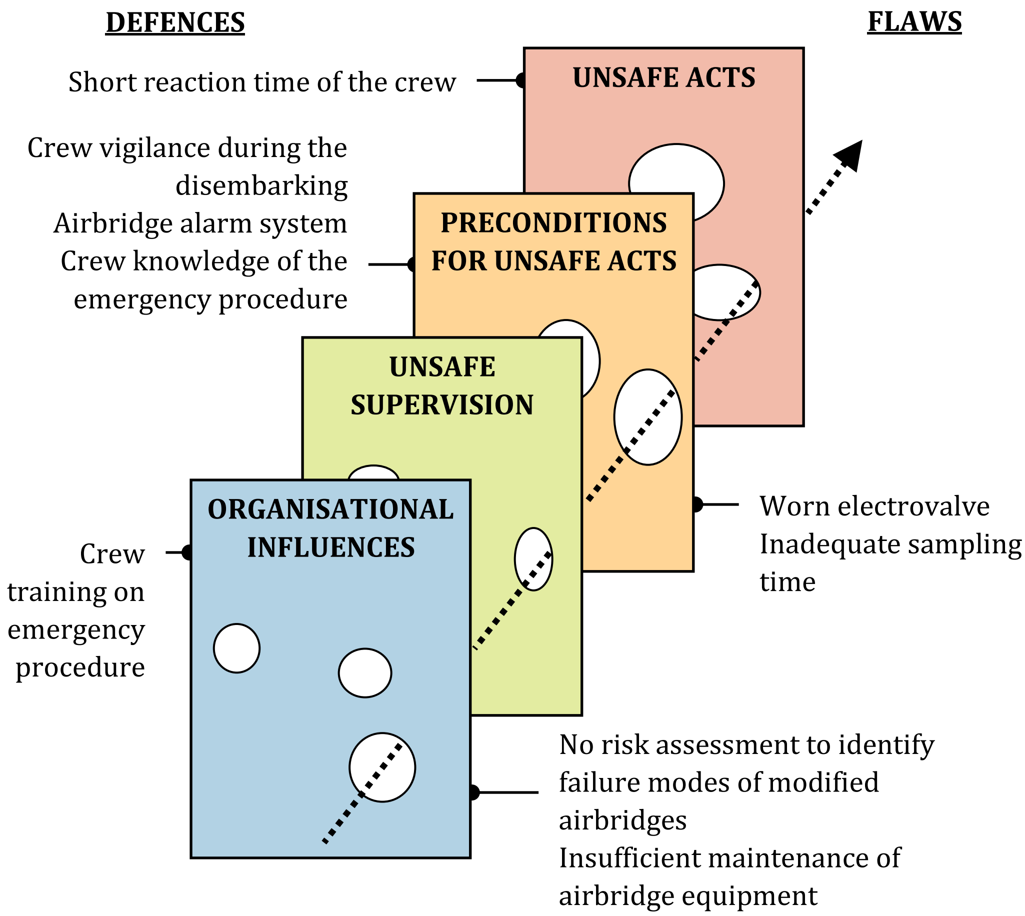

Figure 3.3 Reason's model of the incident

Reason's Model does not provide a taxonomy of the human factors involved in the incident, as it is made clear in Figure 3.3. A revised version of Reason's model, containing the identified HFACS nanocodes is presented in Figure 3.4.

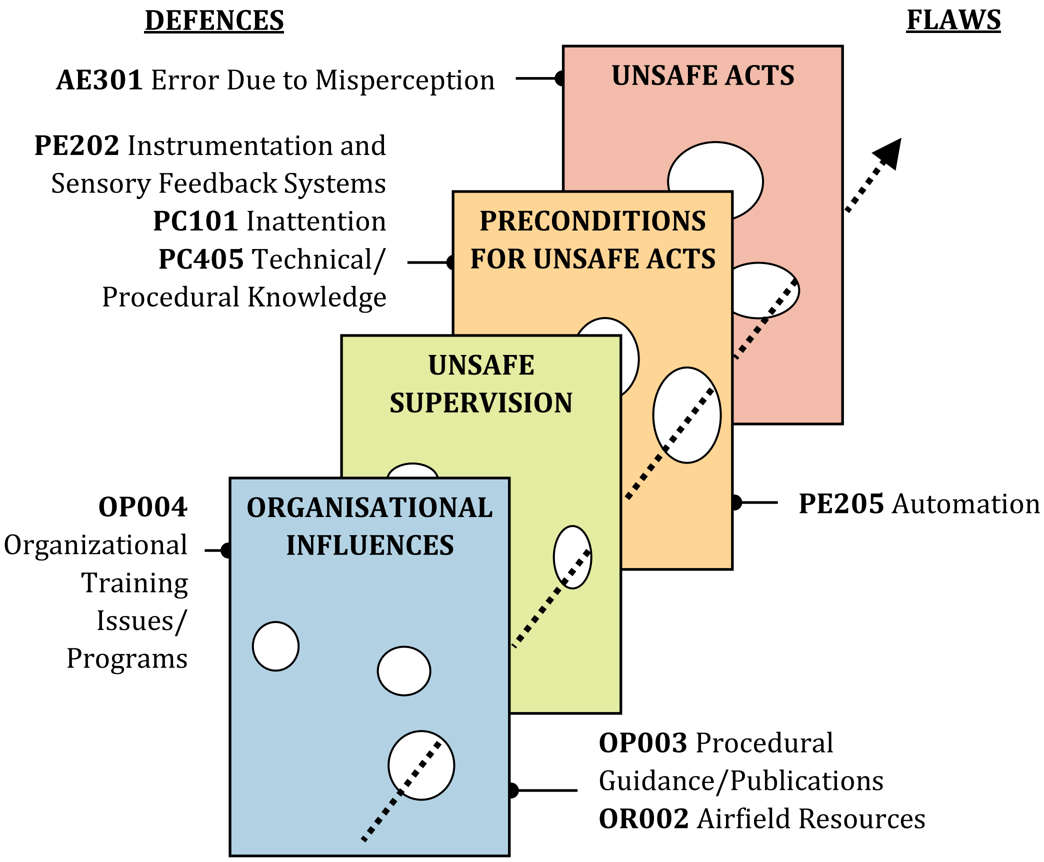

Figure 3.4 Reason's model of the incident with HFACS nanocodes

4. Study of the Incident with FRAM

4.1. Introduction to FRAM

The functional resonance analysis method (FRAM) was developed by Erik Hollnagel in 2012 and it focuses on the variability that lays within every complex socio-technical system. FRAM is based on four principles:

1. **The principle of equivalence of success and failures.** It is based on resilience engineering and it means that failures are the negative side of the need of the system to adapt to ever-changing working conditions. They are not the breakdown of normal system functions. Components of a system are normally able to anticipate risks and critical situations and to respond with appropriate actions; failures originate when this ability is not present.
2. **The principle of approximate adjustments.** The system is surrounded by an environment that continually varies so that the actual working conditions are never the same as the ones specified. Components of the system need to adjust to the variability of resources and requirements to guarantee success but because resources are finite the adjustments are never exact but rather approximate.
3. **The principle of emergence.** Accidents or incidents are rarely caused by the variability of normal performance. Nevertheless, events that are greatly disproportionate, i.e. non-linear, are the product of the unexpected combination of performance variability within the system. FRAM affirms that failures or proper functioning are not resultant but rather emergent as they cannot be traced back to the functioning of specific components.
4. **The principle of functional resonance.** A single function can exceed normal performance limits because variability performance of other function resonates. Instead of spreading through clear and countable cause-effects relationships the consequences may spread through couplings and this is described as functional resonance. This analogy with dynamic systems highlights how this phenomenon is not explicable through simple causal links.

Applying FRAM to an accident or incident scenario allows the analysis of the functions performed within the system and of the way they are interrelated. The objective is to explain how performance variability becomes too high producing an incident or an accident. FRAM is suitable both for post-event investigations and risk analyses.

The first step of the FRAM analysis is to identify the functions performed within the system. Each function is later described through six aspects, that represent the state changes occurring in the system that pertain to that function. These six aspects are:

1. Input (I): the signal that starts the function;
2. Output (O): the result of the function, as an entity or state change;
3. Preconditions (P): a circumstance that must be verified before the function can take place;
4. Resources or Execution Conditions (R): what the function consumes while it takes place (Resource) or a circumstance that must be met while the function takes place (Execution Condition);
5. Time (T): any temporal restriction influencing the function;
6. Control (C): means through which the function is monitored or controlled.

Apart from the six aspects, functions can either be background or foreground functions depending on how in depth they need to be investigated. For background functions, only the Input or the Output is specified. With respect to a given function, other functions can be thought of as downstream functions if they occur afterwards and as upstream functions if they occur in advance.

Next, the variability of the functions is assessed. Variability can be:

1. Internal, if the nature of function itself causes the Output to vary;
2. External, if the environment and the working conditions cause the Output to vary;
3. Due to functional upstream-downstream coupling.

With respect to variability, depending on who or what carries out the function, the function itself belongs to one of the three types: technological, human or organisational. To assess internal and external variability Common Performance Conditions (CPCs) are rated.

Depending on the type of the function, only some of the eleven suggested CPCs are applicable. This is shown in Table 4.1.

Table 4.1 Relevance of Common Performance Conditions based on function type

Common Conditions	**Functions affected**		
	M	**T**	**O**
Availability of resources (personnel, materials, equipment)	×	×	
Training and experience (competence)	×		
Quality of communication (team, organisation)	×		×
Adequacy of HMI and operational support	×		
Availability of procedures and methods	×		
Conditions of work	×	×	
Number of goals and conflict resolution	×		×
Available time, time pressure	×		×
Circadian rhythm, stress	×		
Team collaboration quality	×		
Quality and support of the organisation			×

Once the functions varying due to internal and external variability have been found, the performance of the functions needs to be characterised in terms of time and precision. Because the variability of a function reflects on its Output, this task is carried out evaluating if the Output was too early, on time, too late or omitted as far as time is concerned and if it was precise, acceptable or imprecise as far as precision is concerned.

The next step is the aggregation of variability. Considering a single function, this will receive the Output of its upstream functions in the form of an Input, Precondition, Resource, Time or Control. If such Output varies then this affects the performance variability of the considered function, depending on what that Output represent to the considered function itself. Performance variability of the considered function can either increase, decrease, or stay equal. This step is aided by tables and the FRAM graphic model of the event. The execution of this step is key to understand how the negative event emerged because of functional resonance.

After the completion of the previous steps the safety analyst suggests mitigation measures. Apart from the usual remedies (elimination, prevention, facilitation, protection), FRAM suggests monitoring and dampening. Monitoring of the system is done through indicators whose identification can be aided by FRAM. Dampening is done through the proposal of measures that decrease performance variability of the functions in terms of internal and external variability, as well as variability from upstream-downstream couplings.

Because FRAM can be applied to several field of studies, this last step can be integrated with established methods typically used in different industrial domains to overcome weaknesses of the FRAM. In this work, because FRAM does not provide a taxonomy of human factors, HFACS was used to identify those involved in the analysed event. This was done by identifying HFACS nanocodes applicable to the CPCs marked as inadequate and to the upstream-downstream couplings that cause an increase of performance variability of the downstream function.

The diagram in Figure 4.1 illustrates the steps of a FRAM analysis. The last box is dashed because it is an addition introduced in this study to the original FRAM analysis process.

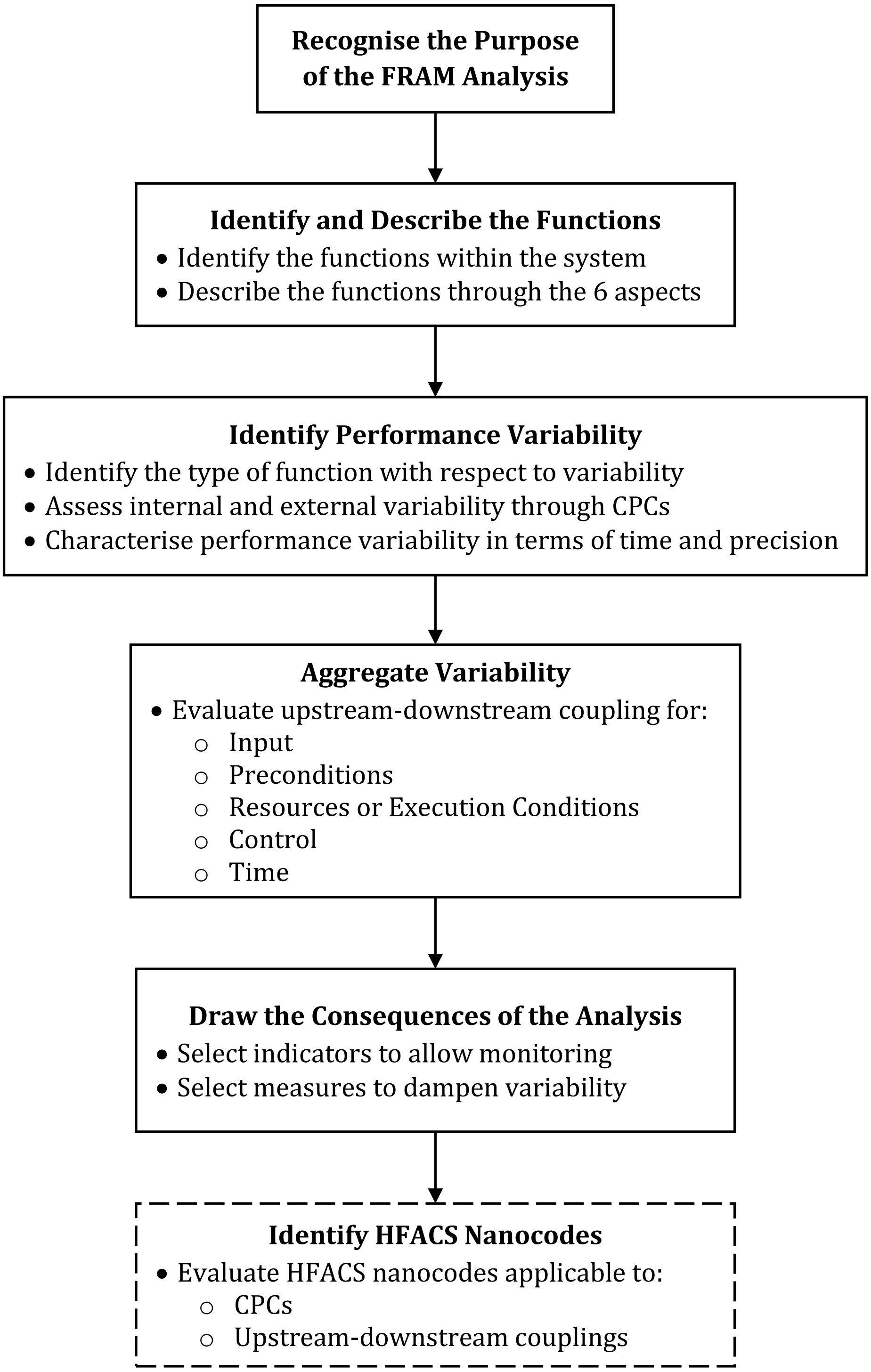

Figure 4.1 Steps of the FRAM analysis

4.2. FRAM Analysis

4.2.1. Identification and description of the functions

The functions performed within the system are identified using the incident report by the Spanish CAA. The identified functions are:

1. Park aircraft;
2. Connect airbridge to aircraft;
3. Authorise disembarking;
4. Disembark passengers safely;
5. Receive passengers;
6. Disembark luggage;
7. Keep airbridge level with aircraft;
8. Renovate airbridge equipment;
9. Maintain airbridge equipment;
10. Evaluate major failure modes;
11. Set sampling time;
12. Train crew;
13. Supervise disembarking.

Each function is described through the six aspects as shown from Table 4.2 to Table 4.14. In the next paragraphs, functions are signalled with "<...>" while aspects are signalled with "[...]".

Functions 1 to 7 consider the usual proceeding of the disembarking of passengers and luggage after the arrival of the aircraft at the assigned parking position.

Table 4.2 FRAM representation of <Park aircraft>

Name of function	**Park aircraft**	**1**
Description	The aircraft was parked at the time of the incident	
Aspect	**Description of aspect**	
Input		
Output	Aircraft parked	
Precondition		
Resource		
Control		
Time		

<Park aircraft> is a background function thus no Input is specified. It serves as the source of the Input of the foreground function <Connect airbridge to aircraft>.

Table 4.3 FRAM representation of <Connect airbridge to aircraft>

Name of function	**Connect airbridge to aircraft**	**2**
Description	This function is performed in coordination by the airbridge operator and the aircraft crew	
Aspect	**Description of aspect**	
Input	Aircraft parked	
Output	Autolevelling system active	
	Airbridge level with aircraft	
Precondition		
Resource		
Control		
Time		

<Connect airbridge to aircraft> has a double Output because once the aircraft is parked the airbridge is brought level with the aircraft, then the airbridge operator activates the autolevelling system.

Table 4.4 FRAM representation of <Authorise disembarking>

Name of function	**Authorise disembarking**	**3**
Description	This function is performed by the captain	
Aspect	**Description of aspect**	
Input	Autolevelling system active	
Output	Disembarking authorised	
Precondition		
Resource		
Control		
Time		

Table 4.5 FRAM representation of <Disembark passengers safely>

Name of function	**Disembark passengers safely**	**4**
Description	As the passengers disembark the aircraft becomes lighter and raises on its landing gear	
Aspect	**Description of aspect**	
Input	Disembarking authorised	
Output	Aircraft raises	
	Passengers safely disembarked	
Precondition		
Resource	Airbridge level with aircraft	
Control	Disembarking supervised	
Time		

<Disembark passengers safely> has a double Output: while passengers are safely disembarked through the airbridge the aircraft raises on its landing gears. The disembarking is supervised by the crew as it is captured by the Control aspect. In addition, the safe disembarking of passengers requires an Execution Condition (or Resource): that the airbridge stays level with the aircraft.

Table 4.6 FRAM representation of <Receive passengers>

Name of function	**Receive passengers**	**5**
Description	This function is performed by the airport terminal building	
Aspect	**Description of aspect**	
Input	Passengers safely disembarked	
Output		
Precondition		
Resource		
Control		
Time		

<Receive passengers> is a background function that is used as the destination of [Passengers safely disembarked], to guarantee the completeness of the model.

Table 4.7 FRAM representation of <Disembark luggage>

Name of function	**Disembark luggage**	**6**
Description	As the luggage is disembarked the aircraft becomes lighter and raises on its landing gear	
Aspect	**Description of aspect**	
Input		
Output	Aircraft raises	
Precondition		
Resource		
Control		
Time		

<Disembark luggage> is a background function that serves as the source of [Aircraft raises]. It is included in the model to recognise that apart from the passengers disembarking, also the unload of the luggage causes the aircraft to raise.

Table 4.8 FRAM representation of <Keep airbridge level with aircraft>

Name of function	**Keep airbridge level with aircraft**	**7**
Description	This function is performed by the autolevelling system controlling the hydraulic circuit	
Aspect	**Description of aspect**	
Input	Aircraft raises	
Output	Airbridge level with aircraft	
Precondition	Airbridge equipment correctly maintained	
Resource	Autolevelling system active	
Control		
Time	Sampling time set	

<Keep airbridge level with aircraft> occurs every time the aircraft raises beyond a certain limit. The autolevelling system moves the airbridge so that it is level with the aircraft, to do so such system needs to be active as captured by the Execution Condition (or Resource). To prevent mechanical failures, the airbridge equipment must be correctly maintained, as it is stated under Precondition. The Time aspect recognises that the activation time of the system is determined by the previously set sampling time.

Functions 8 to 11 consider the tasks originating from the renovation of the airbridge.

Table 4.9 FRAM representation of <Renovate airbridge equipment>

Name of function	**Renovate airbridge equipment**	**8**
Description	The renovation of the airbridge had been recently performed by a joint venture between the Spanish companies Luis Pares & Adelte	
Aspect	**Description of aspect**	
Input		
Output	Airbridge equipment renovated	
Precondition		
Resource		
Control		
Time		

<Renovate airbridge equipment> is a background function: only its Output is stated.

Table 4.10 FRAM representation of <Maintain airbridge equipment>

Name of function	**Maintain airbridge equipment**	**9**
Description		
Aspect	**Description of aspect**	
Input	Airbridge equipment renovated	
Output	Airbridge equipment correctly maintained	
Precondition	Major failure modes known	
Resource		
Control		
Time		

<Maintain airbridge equipment> refers to the maintenance performed after the renovation, i.e. on the modified airbridge configuration. To ensure that such maintenance is properly planned it is necessary to conduct a risk analysis on the new configuration, as described through the Precondition [Major failure modes known], Output of <Evaluate major failure modes>.

Table 4.11 FRAM representation of <Evaluate all failure modes>

Name of function	**Evaluate major failure modes**	**10**
Description	The renovation might introduce new unknown failure modes, it is responsibility of the airport management to draft and validate a risk assessment to mitigate all possible failures of the equipment	
Aspect	**Description of aspect**	
Input	Airbridge equipment renovated	
Output	Major failure modes known	
Precondition		
Resource		
Control		
Time		

Table 4.12 FRAM representation of <Set sampling time>

Name of function	**Set sampling time**	**11**
Description	Sampling time is the measure time of the watchdog that verifies the correct position	
Aspect	**Description of aspect**	
Input	Airbridge equipment renovated	
Output	Sampling time set	
Precondition		
Resource	Major failure modes known	
Control		
Time		

The renovation included the change of the airbridge PLC. The risk analysis of the modified configuration is necessary to set the proper sampling time, as expressed through the Execution Condition (or Resource) of <Set sampling time>.

Functions 12 and 13 relate to the airline, both as an organisation and as the duties directly performed by the crew.

Table 4.13 FRAM representation of <Train crew>

Name of function	**Train crew**	**12**
Description	The crew is trained to achieve a good level of management of emergency procedure	
Aspect	**Description of aspect**	
Input		
Output	Emergency procedure known	
Precondition		
Resource		
Control		
Time		

<Train crew> is a background function, its Output is the Resource of <Supervise disembarking>.

Table 4.14 FRAM representation of <Supervise disembarking>

Name of function	**Supervise disembarking**	**13**
Description	The crew is trained to manage the disembarking	
Aspect	**Description of aspect**	
Input	Disembarking authorised	
Output	Disembarking supervised	
Precondition		
Resource	Emergency procedure known	
Control		
Time		

<Supervise disembarking> produces the Control of <Disembark passengers safely>. While the members of the crew supervise the disembarking, they need to know the applicable emergency procedure, as captured through the Execution Condition (or Resource) of the function.

4.2.2. Identification of performance variability

The functions identified in paragraph 4.2.1 are classified with respect to variability as shown in Table 4.15.

Table 4.15 Type of the functions with respect to variability

Function		**Type**
1	Park aircraft	Human
2	Connect airbridge to aircraft	Human
3	Authorise disembarking	Human
4	Disembark passengers safely	Human
5	Receive passengers	Technological
6	Disembark luggage	Human
7	Keep airbridge level with aircraft	Technological
8	Renovate airbridge equipment	Organisational
9	Maintain airbridge equipment	Organisational
10	Evaluate major failure modes	Organisational
11	Set sampling time	Organisational
12	Train crew	Organisational
13	Supervise disembarking	Human

Functions from 1 to 4, 6 and 13 are of the Human type as they are performed by humans individually or in small groups: the crew, the airbridge operator or the passengers. Functions 5 and 7 are Technological functions because they are performed by inanimate objects, such as the airport terminal for function 5, or machinery and computer software, particularly for function 7. Finally, functions from 8 to 12 are performed by large groups of people whose activity is structured, therefore they are presented as Organisational functions.

Next, for each function the relevant CPCs are evaluated. Four functions have one or more CPCs rated “inadequate”, as presented in Table 4.16.

Table 4.16 Rating of CPCs for functions 7, 9, 10, 11

Function		Type	Common Condition	Rating	Likely performance variability
7	Keep airbridge level with aircraft	T	Availability of resources	Inadequate	Noticeable
			Conditions of work	Adequate	Small
9	Maintain airbridge equipment	O	Quality of communication	Adequate	Small
			Number of goals & conflict resolution	Adequate	Small
			Available time & time pressure	Inadequate	High
			Quality & support of organisation	Inadequate	Noticeable
10	Evaluate major failure modes	O	Quality of communication	Inadequate	Noticeable
			Number of goals & conflict resolution	Adequate	Small
			Available time & time pressure	Adequate	Small
			Quality & support of organisation	Inadequate	Noticeable
11	Set sampling time	O	Quality of communication	Inadequate	Noticeable
			Number of goals & conflict resolution	Adequate	Small
			Available time & time pressure	Adequate	Small
			Quality & support of organisation	Adequate	Small

For <Keep airbridge level with aircraft>, the CPC “Availability of resources” is marked “inadequate”. In fact, this CPC contemplates the lack of working equipment, in this case the electrovalve of the autolevelling system that froze in the open position. The source of variability in this case is internal as it resides inside the function.

For the CPCs rating of the remaining three functions, as the incident report was not detailed enough to draw relevant conclusions, assumptions were made. For <Maintain airbridge equipment> it can be assumed that the variability of the function was due to inadequate instructions and guidelines within the organisation. The same can be expected for <Evaluate major failure modes>. For this very function it can also be assumed that variability came from the inadequate communication between the airport organisation and the companies renovating the airbridges. This last assumption can be transferred to function 11 as well. For functions 9, 10 and 11, as determined for function 7, the source of variability is internal because the identified issues reside within the involved organisations.

For the remaining functions listed below, all the pertinent CPCs are rated “adequate” and the deriving performance variability “small”:

1. Park aircraft;
2. Connect airbridge to aircraft;
3. Authorise disembarking;
4. Disembark passengers safely;
5. Receive passengers;
6. Disembark luggage;
8. Renovate airbridge equipment;
12. Train crew;
13. Supervise disembarking

Based on the CPCs rating the Output of every function is characterised in terms of time and precision. This process is presented in Table 4.17.

Table 4.17 Characterisation of the functions Output in terms of time and precision

Function		**Output**	**Time**	**Precision**
1	Park aircraft	Aircraft parked	On time	Precise
2	Connect airbridge to aircraft	Autolevelling system active	On time	Precise
		Airbridge level with aircraft	On time	Precise
3	Authorise disembarking	Disembarking authorised	On time	Precise
4	Disembark passengers safely	Aircraft raises	On time	Precise
		Passengers safely disembarked		
5	Receive passengers	-	-	-
6	Disembark luggage	Aircraft raises	On time	Precise
7	Keep airbridge level with aircraft	Airbridge level with aircraft	On time	Imprecise
8	Renovate airbridge equipment	Airbridge equipment renovated	On time	Precise
9	Maintain airbridge equipment	Airbridge equipment correctly maintained	Too late	Imprecise
10	Evaluate major failure modes	Major failure modes known	Not at all	-
11	Set sampling time	Sampling time set	On time	Imprecise
12	Train crew	Emergency procedure known	On time	Precise
13	Supervise disembarking	Disembarking supervised	On time	Precise

Functions 7, 9, 10 and 11 had one or more CPCs rated “inadequate”, therefore are the only ones having an Output that is not “On time” and “Precise”. The Output of function 7 is imprecise because the airbridge raised too much. For function 9, the airbridge maintenance came too late to prevent the incident. The risk analysis on the reconfigured airbridge was not carried out so the Output of function 10 was omitted. Finally, the Output of function 11 was imprecise because the sampling time was too long.

It is worth noticing that function 5 is a background function and has no Output while the Output of function 4, <Disembark passengers safely>, is marked as “On time” and “Precise” because the performance variability of the function was determined by functional couplings that are assessed in the following step of the analysis.

4.2.3. Aggregation of variability

Next, the coupling of the performance variability of every function is to be evaluated. In Table 4.18, the Output is analysed in terms of what it represents to the downstream functions. This is indicated by the initial letter of the five remaining aspects – an Output cannot be an Output to another function – in the column "Downstream function". The effect on the performance variability of the downstream function is assessed for every coupling and is summarised as:

- V+, if it increases the variability of the downstream function;
- V=, if it has no effect on the variability of the downstream function;
- V-, if it decreases the variability of the downstream function (damping).

Table 4.18 omits the functions whose Output have no effect on downstream functions.

Table 4.18 Evaluation of upstream-downstream couplings

Function		**Output**	**Variability**	**Downstream function**		**Effect**	
7	Keep airbridge level with aircraft	Airbridge level with aircraft	Imprecise	R	Disembark passengers safely	Inadequate or reduced functioning	V+
9	Maintain airbridge equipment	Airbridge equipment correctly maintained	Too late	P	Keep airbridge level with aircraft	Reduced functioning	V+
			Imprecise				
10	Evaluate major failure modes	Major failure modes known	Not at all	R	Set sampling time	Improvisation	V+
				P	Maintain aircraft equipment	Improvisation	V+
11	Set sampling time	Sampling time set	Imprecise	T	Keep airbridge level with aircraft	Increased variability	V+
12	Train crew	Emergency procedure known	On time	R	Supervise disembarking	Damping	V-
			Precise				
13	Supervise disembarking	Disembarking supervised	On time	C	Disembark passengers safely	Damping	V-
			Precise				

An instantiation of the FRAM model, meaning a representation of the actual couplings leading to the analysed occurrence, is shown in Figure 4.2.

Foreground functions are represented as hexagons connected through the six aspects. Background functions are portrayed as circles, producing or receiving an Output or Input, respectively. The functions that resonated leading to the incident present a sine wave in the hexagon.

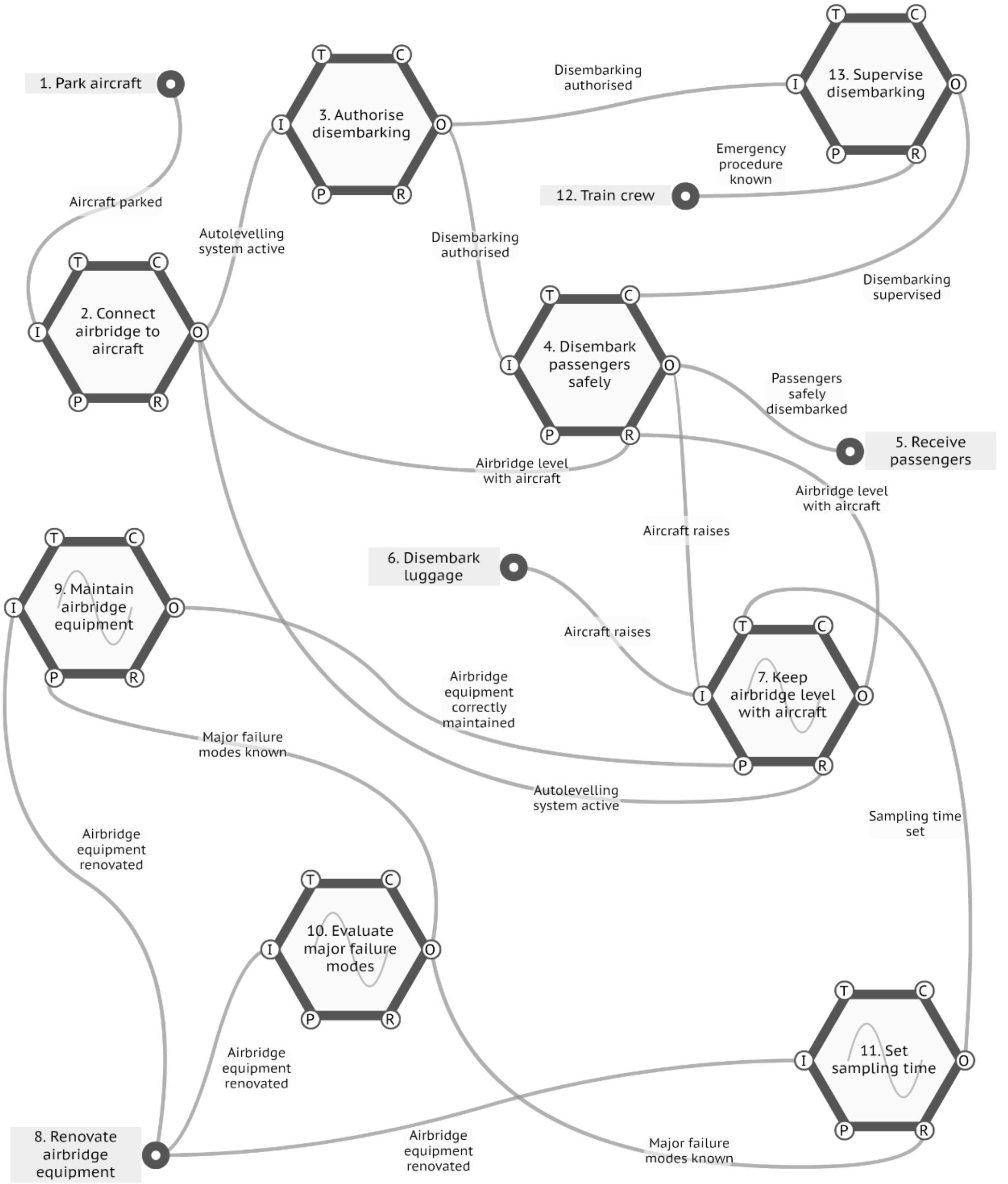

Figure 4.2 Instantiation of the FRAM model of the incident

Looking at the instantiation of the model the functional couplings stand out and it is worth describing them in greater detail.

Starting from the top left of the diagram the background function <Park aircraft> is shown. From this, the usual process of disembarking passengers is represented. Once the aircraft is parked the airbridge is connected, level with the aircraft and the operator activates the autolevelling system. Then, the disembarking is authorised, and the passengers start to disembark safely, thanks to the fact that the airbridge is level to the aircraft as indicated by the Resource of <Disembark passengers safely>. These functions did not vary their performance initially. As the passengers disembark and the luggage is unloaded the aircraft raises, and because the autolevelling system is active, such system keeps the airbridge level with the aircraft. Looking at the model a functional coupling ring is shown between functions 4 and 7. After the initial levelling in <Connect airbridge to aircraft> that provides the Resource to <Disembark passengers safely>, this very function causes the aircraft to raise, triggering <Keep airbridge level with aircraft>. In return this last function guarantees that the Resource of <Disembark passengers safely> is maintained so that the process of disembarking passengers flows regularly until the end, when all the passengers have left the aircraft and have been received by the airport terminal. This last passage is portrayed by the background function <Receive passengers>.

However, in the considered event, this process had to be interrupted as <Keep airbridge level with aircraft> varied its performance and its Output became imprecise, failing to meet the Resource requested by <Disembark passengers safely>.

To understand the emergence of this event, apart from the failure of the airbridge hydraulic system electrovalve, more functions must be considered. The finger had been recently renovated as shown at the bottom left of the diagram, through the background function <Renovate airbridge equipment>. The renovation prompts three functions: 9, 10 and 11. At first it is reasonable to focus on <Evaluate major failure modes>. The configuration of the airbridge had changed but the risk analysis was not carried out. This omission results in the lack of the Precondition of <Maintain airbridge equipment> and the Resource of <Set sampling time>, increasing their performance variability. These two functions are both triggered by <Renovate airbridge equipment> and are functionally coupled with <Keep airbridge level with aircraft>, producing its Precondition and Time control. The reasoning explains how this last function increased so much its variability that it became detectable, affecting the disembarking of the passengers.

Nevertheless, the outcome of the event could have been much worse had the cabin crew not instructed the passengers to sit down and fasten their seatbelts. This is presented at the top right of the diagram. The disembarking authorisation marks the beginning of its supervision from the cabin crew. The crew had been trained to handle the disembarking and the applicable emergency procedure. The <Supervise disembarking>, performed by the crew is functionally coupled to <Disembark passengers safely> through the Control aspect. Because the supervision was precise and quick it represented a damping factor within the system. Indeed, while the <Disembark passengers safely> did increase its performance variability because of the imprecise Resource coming from <Keep airbridge level with aircraft>, such variability did not exceed a certain threshold, meaning none was seriously hurt. This can be explained by the fact that the precise and punctual Control coming from <Supervise disembarking> damped the performance variability, so that the disembarking had to be stopped but in the end all the passengers left the aircraft with only minor injuries.

Figure 4.3 shows the same diagram in Figure 4.2 but the functions that resonated are highlighted in red and the functions that had a damping effect are featured in green.

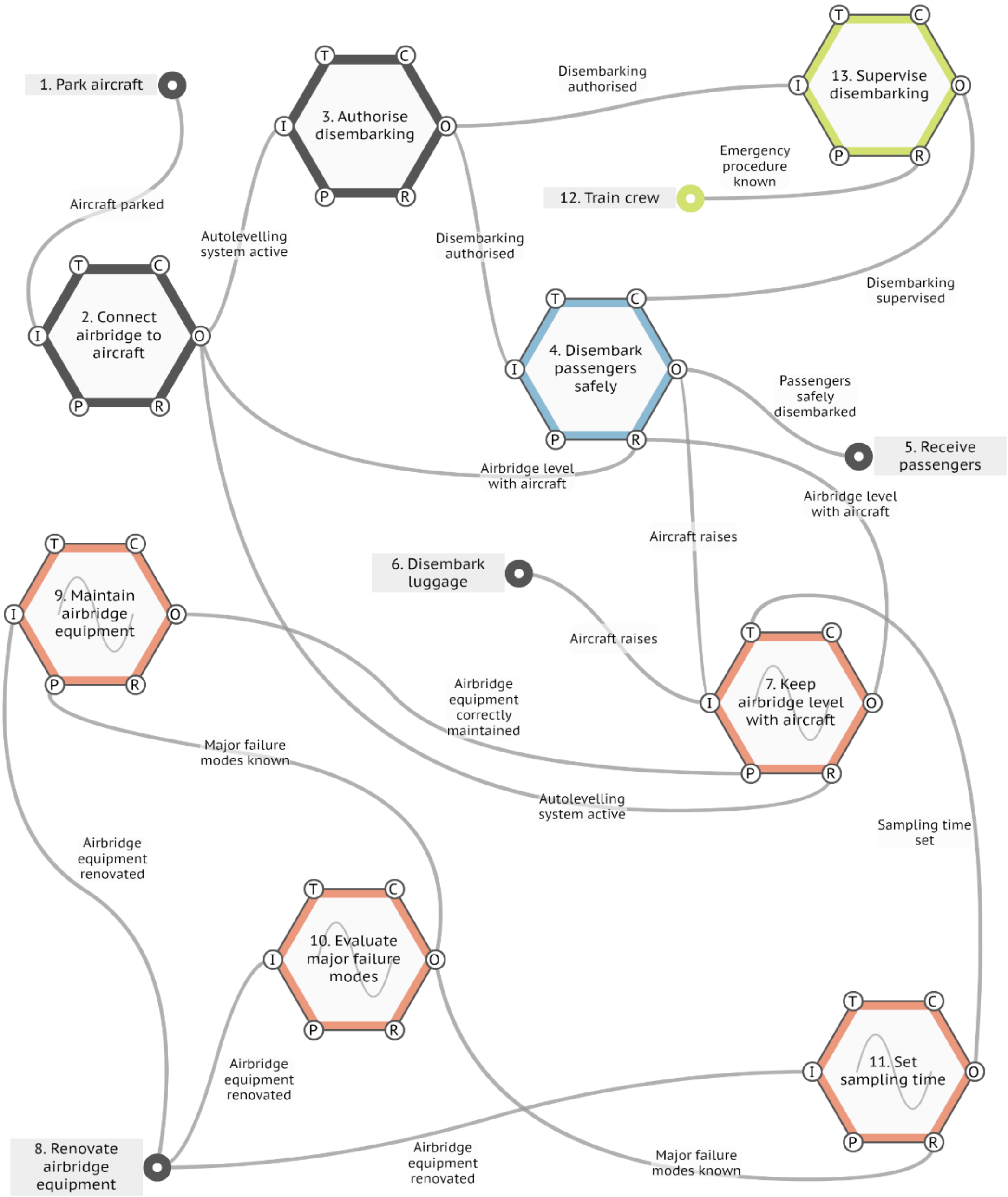

Figure 4.3 Instantiation of the FRAM model of the incident highlighting resonant and damping functions

4.2.4. Consequences of the analysis

The final step of the analysis regards the selection of damping measures to decrease the performance variability of the resonating functions. This part of the analysis is carried out using the HFACS taxonomy. In this, it represents an addition to the original FRAM analysis steps.

HFACS nanocodes are identified based on the CPCs marked inadequate and the functional couplings causing an increase and a decrease of performance variability of the downstream functions. Where possible, the identification of SHELL human factors is used as an intermediate step as the SHELL taxonomy is more approachable as it contains more entries than the HFACS taxonomy. The HFACS nanocodes are then obtained using the SHELL-HFACS matching tool developed by Deloitte. This process is laid out in Table 4.19, Table 4.20 and Table 4.21, respectively.

Table 4.19 HFACS nanocodes based on CPCs

Function		**Type**	**Common Condition**	**SHELL Human Factors**	**HFACS**
7	Keep airbridge level with aircraft	T	Availability of resources	Equipment failure	PE205 Automation
9	Maintain airbridge equipment	O	Available time & time pressure	Operational supervision	SI001 Supervision Inadequate
			Quality & support of organisation	-	OC001 Organisational Culture
10	Evaluate major failure modes	O	Quality of communication	Communication content	PP106 Communicating Critical Information
			Quality & support of organisation	-	OC001 Organisational culture
11	Set sampling time	O	Quality of communication	Communication content	PP106 Communicating Critical Information

Table 4.20 HFACS nanocodes based on functional couplings increasing variability

Function		Output	Downstream Function		SHELL Human Factors	HFACS
7	Keep airbridge level with aircraft	Airbridge level with aircraft	R	Disembark passengers safely	Airfield Facilities	OR002 Airfield Resources
9	Maintain airbridge equipment	Airbridge equipment correctly maintained	P	Keep airbridge level with aircraft	Servicing and inspection	OP003 Procedural Guidance and Publications
10	Evaluate major failure modes	Major failures modes known	R	Set sampling time	Standard operating procedure	AV002 Violation Routine
			P	Maintain airbridge equipment	Manuals	OR008 Informational Resources/ Support
11	Set sampling time	Sampling time set	T	Keep airbridge level with aircraft	Computer software	PE205 Automation

Table 4.21 HFACS nanocodes based on functional couplings decreasing variability

Function		Output	Downstream Function		SHELL Human Factors	HFACS
12	Train crew	Emergency procedure known	R	Supervise disembarking	Emergency Procedure Training	OP004 Organizational Training Programs
13	Supervise disembarking	Disembarking supervised	C	Disembark passengers	Standard Operating Procedure	PC405 Procedural Knowledge

The HFACS nanocodes listed in Table 4.19 and Table 4.20, and the relative descriptions, can be used as the starting point to propose damping measures and barriers within the system to avoid the repeating of such negative occurrence. On the other hand, HFACS nanocodes presented in Table 4.21 are the human factors that served as damping factors. The description of these nanocodes can be used to propose facilitation measures to prevent major injuries to passengers in similar events

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5. Comparison Between FRAM and SHELL-HFACS Analyses

After the incident has been studied by means of the established SHELL method and the more innovative FRAM, the results can be compared.

First, the outcomes of the analyses are considered. This part will deal with the human factors identified using the HFACS taxonomy in the two studies. The HFACS nanocodes are useful in providing a common ground to base the comparison on. Table 5.1 shows the determined HFACS nanocodes; the ones representing effective barriers are marked with [EB].

Table 5.1 Comparison of the HFACS nanocodes identified in the SHELL and FRAM analyses

HFACS Nanocodes		**SHELL**	**FRAM**
Organisational influences			
OR002	Airfield Resources	×	×
OR008	Informational Resources/Support		×
OP004	Organizational Training Issues/Programs [EB]	×	×
OP003	Procedural Guidance/Publications	×	×
OC001	Organisational Culture		×
Unsafe Supervision			
SI001	Supervision Inadequate		×
Preconditions for Unsafe Acts			
PE202	Instrumentation and Sensory Feedback Systems [EB]	×	
PE205	Automation	×	×
PC101	Inattention [EB]	×	
PC405	Technical/Procedural Knowledge [EB]	×	×
PP106	Communicating Critical Information		×
Unsafe Acts			
AE301	Error Due to Misperception [EB]	×	
AV002	Violation Routine		×

The results of the identification of the human factors involved in the incident using the two methods are similar. This gives an indication that FRAM does not bring to results that are substantially different from the ones obtained with more widely used methods such as SHELL and Reason's model. Both methods can identify organisational issues leading to the incident and the positive contribution given by the crew in preventing more serious consequences.

The main differences reside in the way the two methods represent the considered system and how they bring the analyst to the proposal of the necessary safety recommendations.

One of the main differences is the way the two methods represent the considered system. According to SHELL the system is made up of five blocks, as presented in Figure 3.1. Reason's model sees an event or system as four sequential causal domains, shown in Figure 3.3, in which flaws and defences can be identified. These two models are applicable to every event or system being analysed. This does not occur with FRAM. The method does not provide a universal model, instead it outlines the steps necessary to build a model that is specific for every system or event analysed.

Another difference is the way the system is considered in building the model. Since the beginning of the analysis, SHELL and Reason consider the flawed system, pushing the analyst to detect the causal links leading to the adverse event. In opposition, FRAM requires that the model reflects the system in its everyday working conditions. This eases the task of the analyst in the first stages of the incident or accident study, as the enquiry on why things went wrong is postponed. It also allows to make considerations on the daily functioning of the system.

In addition, the way the two methods explain the origin of an incident or an accident is contrasting. According to SHELL a negative occurrence is the result of the mismatch of the interfaces between the individual and other people, the environment, software and hardware. Reason's model defines four causal domains in which the presence of flaws can cause an accident or an incident. In both cases causes can be clearly identified within a system and relationships between events and components, particularly in Reason's model, are considered linear. So, the adverse event is seen as the result of a series of evident causes. This, in turn, makes the obtained model easily tractable and the issuing of mitigations more immediate.

On the other hand, FRAM sees both positive and negative events emerging from couplings between the functions of the system, whose performance is ever-changing, i.e. variable. Couplings are momentary because they depend on the context in which the system operates and the performance variability of the functions. Performance variability may be what leads to an adverse event but according to FRAM it is also necessary to keep the system functioning in response to changes in the working context. So, causes are hardly identifiable as they are transitory and reside in what usually makes the system deliver an everyday acceptable performance. The system is seen as non-linear and intractable. At first, this could pose a challenge to the analyst in finding suitable mitigation measures.

6. Conclusions

The analysis method outlined in ICAO Circular 240-AN/144, based on SHELL and Reason's model are still valid in investigating human factors conditions in aviation incidents and accidents. Nevertheless, it could become inadequate as systems complexity grows. FRAM on the other hand, provides a way to take such complexity into account. Through a FRAM analysis, analysts can assess the relations existing among the functions of the considered system. They can evaluate its resilience, the ability – or inability – of its functions to absorb and damp the inevitable performance variability coming from other functions and propagating through functional couplings. Ultimately, it shifts the focus from failures within the system to the everyday performance variability that all real systems encounter in adapting to the actual working conditions.

A quality of FRAM is the scheme it gives the analyst to create a model of the considered system in its functioning condition. The model is specific for every system analysed and can be graphically presented to better assess functional couplings. This specificity, in return, could also be considered a downside of FRAM. The graphical representation is often necessary since the first stages of the analysis to understand and verify the adequacy of the model in describing the examined system. Its development might require additional time and the use of dedicated software. Also, when many functions are considered the developing of the model could arise confusion and be time consuming. A solution to this comes from the fact that FRAM does not prescribe a certain depth level in the description of the system. So, to make the model more manageable the analyst could merge multiple low-level functions to create a single high-level function, thus simplifying the model.

Anyway, the availability of a model that represents the functioning system makes the first part of the analysis of the adverse occurrence more traceable. The model itself becomes a reference that can be used throughout the analysis to understand the origin of the adverse event. In addition, building a model that does not focus on the causes of the incident or accident allows to eliminate part of the subjectivity usually involved in safety analyses. The FRAM representation of the system through the decomposition into functions follows clear rules. With the help of experts, the analyst can build a model that is mostly objective in describing the system. FRAM then guides the analyst in assessing performance variability coming from internal and external sources using CPCs that are clearly defined and descripted. Next, the role of functional couplings in leading to an accident or incident is considered. At this point though, functional couplings inside the system have already been determined and they convey more information than simple causal links. The analyst is guided in determining how adverse events emerged and the impact of subjectivity on the results of the analysis is potentially reduced.

The main weakness of FRAM lies in the proposal of mitigation measures or, according to FRAM, damping measures. The system is seen as a dynamic entity, featuring non-linear relations with multiple inputs and multiple outputs. This characterisation makes the recommendation of safety measures difficult. The analyst would have to consider multiple linked variables at the same time, and this would mean an increase in the time spent for the analysis. This, in turn, would determine a high cost of the investigation both in economic terms and, more importantly, in social terms. Indeed, the incident or accident analysed could reoccur before the issuing of mitigation measures. However, as FRAM has several fields of applicability, it gives the analyst a certain degree of freedom in selecting the most appropriate method to develop safety recommendations.

In this study, a method to come up with mitigations at the end of a FRAM analysis is presented. It is based on the linearization of the functional couplings within the system. By doing this, every coupling is considered individually, along with internal and external sources of performance variability. The corresponding human factors become easily identifiable and make the issuing of mitigations easier and faster. In particular, the HFACS taxonomy was used because, as previously detailed, its entries have a description enclosed that decreases subjectivity in issuing safety recommendations.

In conclusion, the main objective of this study was to assess if – and how – FRAM could be a useful tool in the accidents and incidents investigations conducted according to ICAO Annex 13. FRAM has proved to be a valuable instrument, giving a framework to build a specific model of the analysed system in its everyday functioning. This model allows the safety analyst to consider performance variability of the functions inside the system. Above all, the use of a FRAM model could potentially decrease the influence of the investigator subjectivity on the analysis. However, FRAM does not give a structured process to facilitate the proposal of mitigation measures. To compensate for it, this study proposes the incorporation of the human factors taxonomy given by HFACS in the last part of the FRAM analysis.

This study could be further developed conceiving specific CPCs for the aviation industry to better assess internal and external variability in the FRAM analysis.

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