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Modeling air accident investigation methodologies: from the technical factor to the human factor

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Summary

Aircraft is the safest means of transport but an error or a misbehave could lead to a catastrophe. Statistical data show a decrease in accidents due to technical factors and an increase caused by human factors noticeable in 70% of accident cases. Consequently, the sector of investigation had to adapt to this change by using better-performing models. Human factors in aviation are involved in the study of human's capabilities, limitations, and behaviors, as well as the integration of that knowledge into the systems that we design for them to enhance safety, performance, and general well-being of the operators of the systems.

The following thesis focuses its attention on the human factors study and on the development of a model that is best suited to the analysis of specific accidents. In this regard, it was necessary to conduct detailed research on the different methods.

A statistic, based on the IATA (International Air Transport Association) 2022 report, is given in this work. The acquired data have permitted to determine the main category of accidents which is the loss of control in flight.

Follow a descriptive section of a new accident model, defined as a hybrid, is given. The new hybrid model helps to unravel the mishap causes and it has as its strength the passage through various analyses. To support the proposed model, studies have been conducted on three accident cases that have the human factor as root cause.

Since the human factor that cannot be eliminated, the new method will have limitations, but these can be overcome thanks to the synergetic collaboration of the various described approaches.

Con immenso piacere posso dire di aver concluso questo percorso universitario dopo cinque anni. La gioia e la felicità sono immense. Un grazie particolare va a chi mi ha permesso di affrontare questo argomento a conclusione dei miei studi. In primis ringrazio il Professore Maggiore per essere stato disponibile nel seguirmi dedicandomi materiale e tempo, rispetto ai suoi impegni.
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Chapter 1

Introduction

1.1 Preliminary standards of accident investigation

Before an accident occurs, many incidents and failures may indicate the presence of risks to the system's safety. To enhance the system's safety, it is essential to identify all events to facilitate analysis and promote corrective actions.
The investigations are the best solution to identify probably security deficits, that led to accidents and, which, if not eliminated, reoccur.
Decades of accident investigations have shown that many incidents could have been prevented. This suggests that safety measures were either ignored, bypassed, or inadequate. Investigating and addressing these aspects is a fundamental objective of accident investigations.
The investigation aims to detect and identify any abnormal or incorrect human behavior. It verifies whether these behaviors are influenced by past events or persistent conditions. Therefore, it is crucial to establish the chain of causes and effects. This can help create prevention barriers and reduce the likelihood of errors being repeated.

1.1.1 ICAO Regulations

The safety of the operations of air carriers and their aircraft is guaranteed by a set of international rules and controls. The rules are based on the standards and recommendations contained in the Technical Annexes of the ICAO.[21][22]

ICAO Annex 13

Annex 13 [14] sets out the rules on accident notification, investigation, and reporting. It also sets out the process leading to the issue of a preliminary accident investigation report and a final report. Annex 13 states that its purpose is not to attribute blame but to prevent accidents. It also provides for the creation of an Accident Data Report.
Chapter 1 defines an accident as:
“an occurrence associated with the operation of an aircraft which takes place between the time any person boards the aircraft with the intention of flight until such time as all such persons have disembarked, in which a person is fatally or seriously injured . . . , the aircraft sustains damage or structural failure . . . , or the aircraft is missing or is completely inaccessible”.
An incident is defined as:
“an occurrence, other than an accident, associated with the operation of an aircraft which affects or could affect the safety of operation”.
This definition is useful in determining the criteria for reporting the occurrence to the investigation authority and in identifying when an investigation should be conducted.
It also defines the concept of safety recommendation as:
"A proposal of an accident investigation authority based on information derived from an investigation, made with the intention of preventing accidents or incidents which in no case has the purpose of creating a presumption of blame or liability for an accident or incident. In addition to safety recommendations arising from accident and incident investigations, safety recommendations may result from diverse sources, including safety studies."

ICAO Annex 19

ICAO Annex 19 [16] contains the general provisions to be applied in the field of security and therefore requires each state to have a safety program.
Chapter 1 defines safety as:
"The state in which risks associated with aviation activities, related to, or in direct support of the operation of aircraft, are reduced and controlled to an acceptable level."

1.2 Human Factors

The concept of human factors has been widely used since the last century. With the development of knowledge, it can now be applied to the field of aviation safety.
Initially, the focus was on the impact of noise, vibration, and acceleration forces on individuals. However, over the past fifty years, the scope of research has broadened to include cognitive aspects of aviation tasks, such as decision-making, the decision-making process, flight deck and cabin design, communication, software, and operational manuals. Aviation psychology has also been applied to staff selection, training, and accident investigations.
The human factor is a multidisciplinary nature. At the individual level, information is taken from psychology to understand how people process information and make decisions.
One definition of human factors, proposed by Professor Elwyn Edwards, declares that "Human Factors is concerned to optimize the relationship between people and their activities, by the systematic application of human sciences, integrated within the framework of systems engineering".[4][2]
In Europe, the terminology used for describing the concept of human factors is "ergonomics", which could be attributed to biomechanical and biophysical aspects. Today the terms human factors and ergonomics can be used interchangeably. Those refer to all aspect that affects human performance in the workplace.

1.2.1 Human factors in the aviation world

Aircraft is considered the safest means of transport. It is worth noting that after years of continuous decrease, the accident rate has leveled off. Adequate measures must be taken to prevent accidents, especially with the increase in air traffic. The cake chart below, figure 1.1, includes all the aspects of human factors, like maintenance, air traffic control, and operations. Because aviation is continually improving, aircraft are seldom the cause of an accident. It is more probable that the root cause of an accident is humans. In particular, 75% of air accidents are attributed to human error. Therefore, the best opportunity for safety improvement is to understand and manage the human factors that create safety risks.

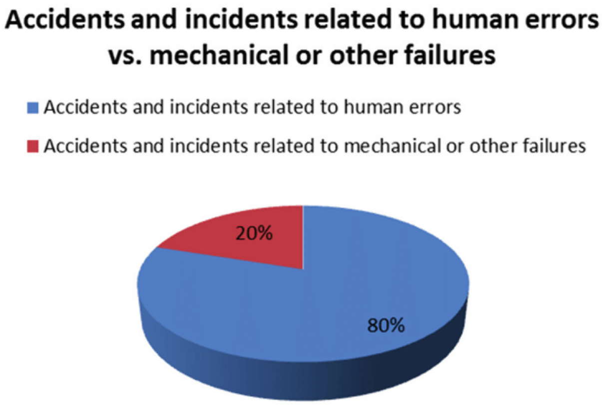


Figure 1.1: Human or technical error accident diagram

Although safety standards are high, the civil aviation system still contains latent conditions that can result in accidents. Statistics on accidents demonstrate that human performance deficiencies were either the cause or a contributing factor to these accidents. Human errors indicate security system deficiencies. Therefore, it is necessary to improve the system's supervision effectively. It is not surprising that human error has been identified as a major factor in almost all aviation accidents and incidents.
Understanding the context of human error remains one of aviation's greatest challenges. If it is possible to understand the reasons why humans make mistakes, it can develop better strategies to avoid errors, control them, and resolve them.
In the beginning, human errors were related to the operating personnel, controllers, pilots, and mechanics. But over time, this concept passed to refer to the entire aviation system.

1.2.2 ICAO actions

Because of the tragic nature of accidents resulting from a lack of knowledge about human factors, ICAO has introduced training on them to develop greater awareness in the aviation community.
The training introduced was on the training and licensing requirements of Annex 1 (1989), the operation of aircraft requirements of Annex 6 (1995), and the airworthiness requirements of Annex 8 (2001).

Human error

Human error is an action that leads to unintended consequences. They cannot be controlled but managed.
It is necessary to define the types of errors:

Unintentional : is an unintentional error (slip) caused by insufficient knowledge or inattention.

Intentional : is like a violation, a deviation from correct procedures, norms, and standards.

Active error : is the real event that results in an accident.

Latent error : the presence of which causes the active error.

1.3 A brief introduction to accident statistics

In 2021 there was a recovery with modest growth in passenger numbers, 49% less than pre-pandemic standards.
2022 was characterized by a rise in accident and accident rates. This makes sense because from 2021 to 2022 there was an accident increase of 33.3% due to flight increasing thanks to the reduction of pandemic restrictions.
The accident rate is a general index of the safety performance of air transport operations. It is based on commercial operations involving aircraft with MTOW over 5700 kg.
ICAO data show that the 2022 accident rate, of 2.05, had an increase of 6.3% concerning the value in 2021, 1.93.[5]
Between 2018 to 2022 annual accident trend significantly decreased. The highest number of accidents was in 2019 when occurred 114 accidents. During the period from 2020 to 2021, it fell due to COVID-19 restrictions. In 2022 the trend started to recover, the air traffic increased, as well as the number of accidents and fatal accidents. There also recorded a growth in the number of fatalities.
The charts below, figures 1.2 1.3 1.4, show the evolution of accidents and fatal ones in the last years and expose an increase of 25% of the flight numbers from 2021 to 2022, approximately about 26.8 million flights. Importantly, the reduction in accidents is due to an improvement in the aircraft and its onboard systems.[7]

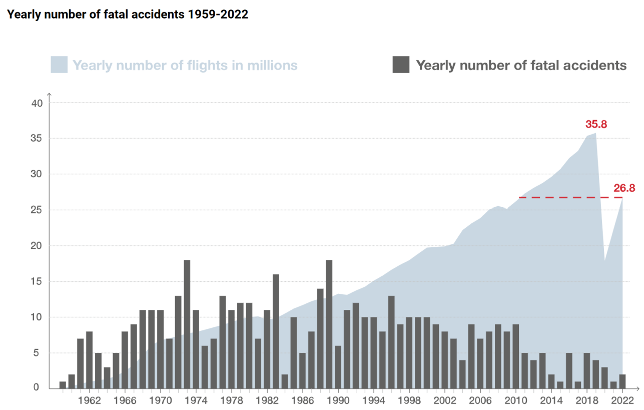


Figure 1.2: Evolution of the number of flight and fatal accidents

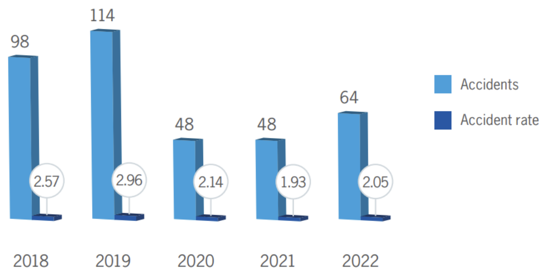


Figure 1.3: Accident records: 2018–2022 scheduled commercial operations

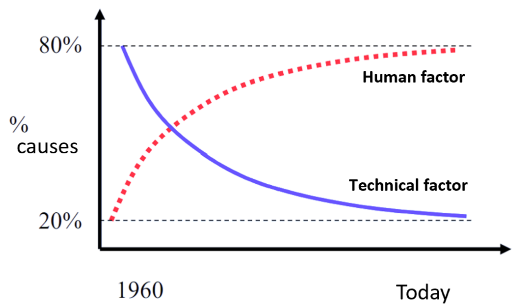


Figure 1.4: Percentage of the human factor in accidents

It is important to note that 50 % of these accidents occurred during the approach and landing phases of flight. These phases are complex and involve a combination of high workload and unpredictable events, which can create a complex interaction of factors that may lead to an accident.
88 % identified the crew as a causal factor and 76 % found humans as the primary accident causes. Only 11 % depended on the aircraft's problems. The 41 % found lack of position awareness in flight as a key factor that involved fatal accidents.

1.3.1 Accident categories

ICAO Member States are required to report accidents and fatalities, that occurred in their regions, following ICAO Annex 13 through the ADREP ICAO system. For accident classification is common to use the taxonomy CAST/ICAO Common Taxonomy Team (CICTT). [15]

In 2022, as shown in the chart 1.5, the European and North Atlantic Region (EUR/NAT) and Middle East Region (MID) did not record fatal accidents. Two of these occurred in the Asia Pacific Region (APAC) according to 83% of total fatalities. The Eastern and Southern African (ESAF) Region, North American, Central American, and Caribbean (NACC) Region and the South American (SAM) Region each experienced one fatal accident, collectively resulting in 14% of fatalities. The last two accidents happened in the West and Central African Region (WACAF).
Looking at categories and not regions, the graph 1.6 shows that the turbulence encounter (TURB) caused the major number of accidents, followed by runway excursion (RE). The line is cumulative and increases as incidents are added. In 2022 occurred 7 fatal accidents caused by: controlled flight into or toward terrain (CFIT), loss of control in-flight (LOC-I), ground handling (RAMP), runway incursion (RI), turbulence (TURB), and unknown or undetermined (UNK). The description of the acronyms can be found in 5.1 [3]

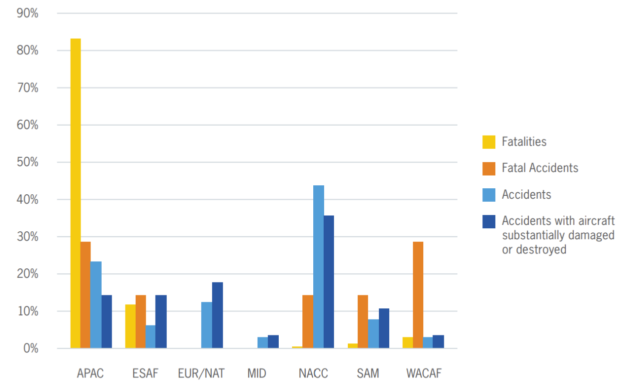


Figure 1.5: Accident overview by ICAO region in 2022

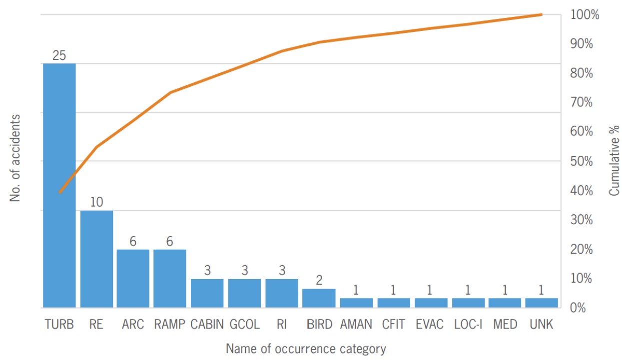


Figure 1.6: Total accidents by occurrence category in 2022

However, if we focus on the last 20 years, it is possible to identify Loss of Control In-flight (LOC-I) as the primary cause of aircraft accidents. Aircraft technology advancements have resulted in a decrease in the number of accidents. Considering Airbus data, to reduce the accidents, that occurred by LOC-I, they introduced flight envelope protection. The introduction of a Flight Management System (FMS), navigation display, and Terrain Awareness and Warning System (TAWS) helped to reduce the CFIT accident rate. Also, the landing performance-based warning systems, such as the Runway Overrun Protection System (ROPS) helped to reduce the RE accident rate.

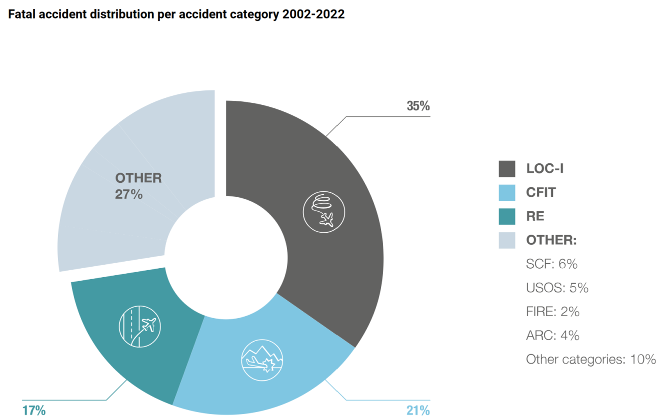


Figure 1.7: Fatal accident distribution per accident category 2002-2022

1.3.2 Main accident errors

As previously stated, accidents are primarily caused by human factors, such as decision errors in the cockpit, maintenance errors, design errors, and errors related to human-machine interaction.

Human-Machine interaction error

The introduction of automation to reduce pilot workload and increase operational efficiency has become a significant cause of accident risk. Improper use of automation can lead to disaster, as pilots may become overly reliant on it and handle situations superficially. To address this issue, it is necessary to improve pilot training.

Decision-Making error

These errors are typically errors of intention, where the decision-maker acts based on their understanding of the situation. The error lies in the decision-making process or knowledge base.
It is often possible to trace the origin of this error to the decision to continue the flight even if the situation is not safe. Sometimes, due to underestimation of the error, the consequences are not evaluated, which can conflict with the safety and success of the mission.[17]

Maintenance error

80% of maintenance errors are due to human factors. It contributes positively to accidents when it is not carried out properly, when installations are incomplete, and when control procedures (checklist) are incorrect.
Transport Canada identified twelve factors, called "dirty dozen" that contribute to maintenance errors.[1] They are shown in the figure below and described in Appendix A:

Figure 1.8: Dirty Dozen

Chapter 2

Methods

This paper analyses four types of aircraft accidents: cockpit decision error, design error, maintenance error, and other causes. The study will use appropriate models to investigate these causes.

2.1 History of methods

Accident model analysis is the base of accident investigation. These methods follow technological evolution through changes. This proves the capability of the accident model to prevent risks, and its capacity to evaluate them.[24][19]
Changes are listed below:

- Rapidity in technological change, thus the introduction of new unknowns.
- Changing nature of accidents, because digital systems have introduced new failure modes and sometimes redundancy can increase the risk of accidents by increasing the complexity of the system.
- new type of hazards.
- Increasing system complexity.
- Increasing complexity of interaction human-machine.
- Changing regulatory and public views of safety, now the governance could control the risks.

As the figure 2.1 shows there are different types of accident models but to understand it is just necessary to divide them into two categories: linear accident method and non-linear accident method. The initial type is

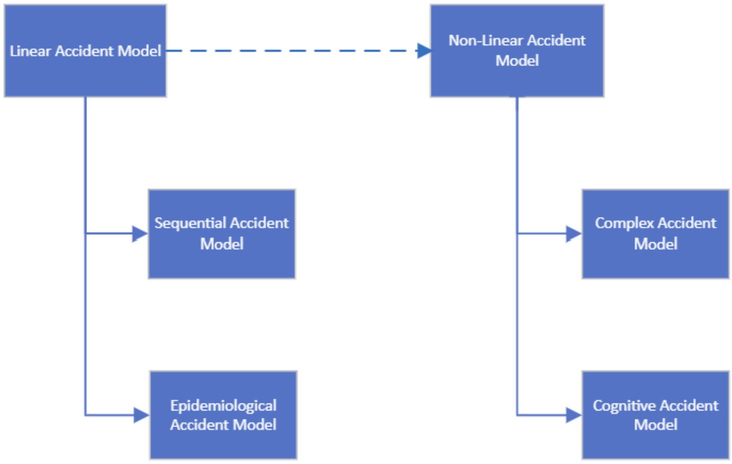


Figure 2.1: Method development chart

defined by its simplicity, a linear sequence of events, and the accident's origin in physical component failures or human error. Its primary focus is on studying the events that occurred immediately prior.
The sequential model recognizes a main event that led to an accident. This is the result of a cause which if identified or removed does not bring to an accident.
The epidemiological model considers the accident as a concurrence of factors. There are latent failures, associated with organizational ones, real events, and active failures.
The second one is characterized by a change in the general view, it is the union of systems and it is more complex.
On the one hand, the concept is systemic, involving an analysis of the factors that succeed in a given space and time. On the other hand, new technological developments have expanded human work beyond physical actions to include knowledge-based and cognitive tasks.
Overall, there is a focus on human-machine interaction.

2.1.1 Typical analysis methods

	Advantages	Disadvantages
SHELL	• Emphasizes the human factor. • Useful in giving a visual sense of how elements of these systems interact. • Useful to reduce errors and prevent accidents.	• Do not value interfaces outside human factors. • Basic help understanding human factors.
REASON	• Recognize latent failure. • Recognize that accidents are caused by an interaction of more failures than only one.	• A simplistic vision of accidents. • Static analysis of organizational factors. • Linear sequence
HFACS	• Consider all aspects of human factors. • Its scope is to discover the failure causes and not to blame.	• Explain the accident's causal factors but not give the measures to prevent it.

Figure 2.2: Comparison of classical models

Accident resolution can be achieved by using performance methods tailored to different types of accidents. The introduction of errors caused by human factors led to the birth of models that consider humans, as the system center.

In particular, in the SHELL model, the focus is on the relationship between humans and systems. A block diagram was created to define, in a graphic way, the interfaces. Each mismatch could lead to an error. The main problem is the non-assessment of the interaction outside the system.[6]

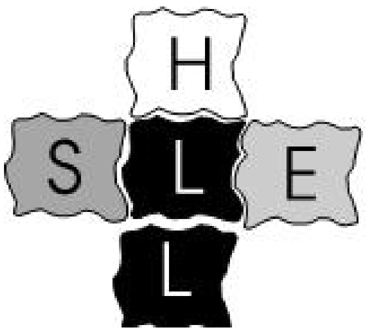


Figure 2.3: SHELL model block diagram

Liveware is the hub of the SHELL model. The remaining components must be adapted and matched to this central component.

Liveware-Liveware, involves the interaction between the central human operator and any humans in the aviation system. Human-human interaction can positively or negatively influence performance.
Liveware-Environment, the interaction between humans and the external or internal environment. It is the environment to adapt to humans.
Liveware-Hardward, the interaction with machine, also known as HMI, human-machine interface. The user may never notice an L-H deficiency, even though it eventually leads to disaster because the natural human characteristic of adapting to L-H mismatch is to mask that deficiency, but not eliminate its existence. This constitutes a potential danger that designers should pay attention to.
Liveware-Software, the relationship between humans and procedures. Sometimes it is difficult to recognize and solve these problems.

Another accident model useful for solving a lot of accidents is the Reason Model. It is simple and based on a system failure described through the image of Swiss cheese. According to this metaphor, in a complex system, the hazards are blocked through barriers. Each barrier presents unintentional holes. Some of them are due to active failures and the others are due to latent failures. These weak points are inconstant, they could open or close without a specific scheme. When all the holes are lined up it is possible to arrive at the damage.[12]

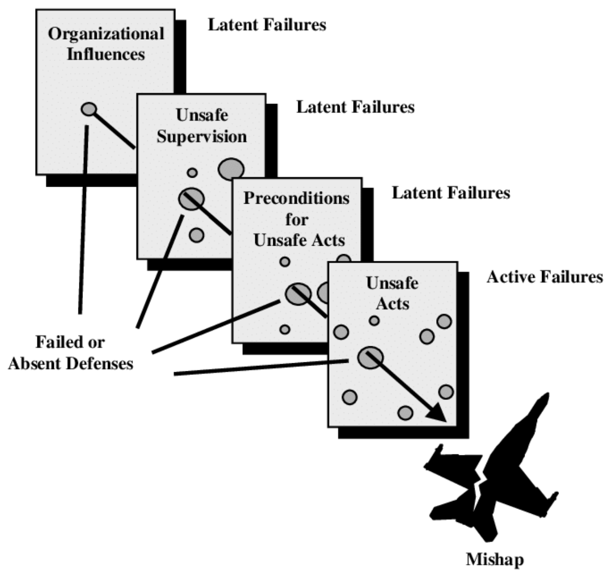


Figure 2.4: Swiss Cheese model rappresentation

Reason supposed four cheese slices that represent organizational influences, unsafe supervision, preconditions for unsafe acts, and unsafe acts. This is the common point with another accident method developed by the United States Department of Defence, the HFACS, Human Factor Analysis Classification System. It is characterized by the use of nano codes that could describe all human errors, violations, or deficiencies. Its scope is to discover the failure causes and not to blame someone.[26]

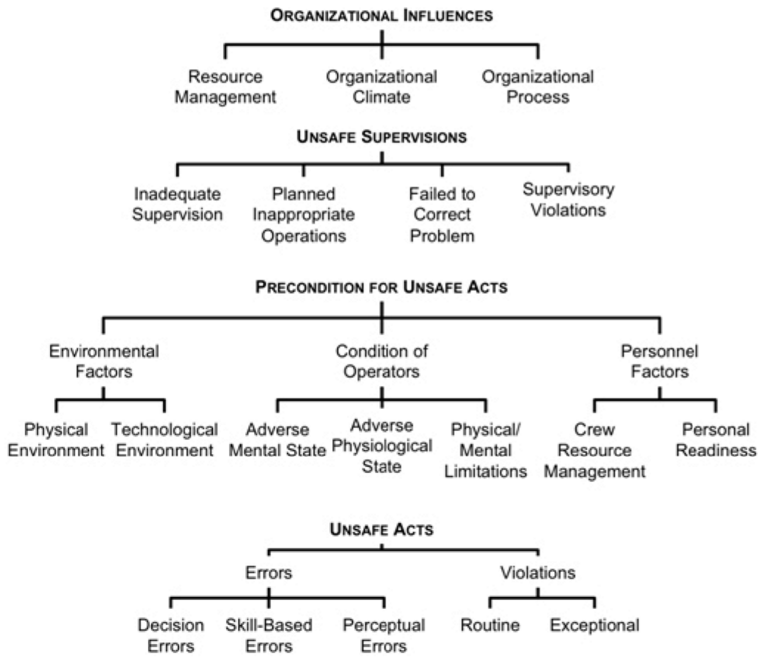


Figure 2.5: HFACS diagram

2.1.2 Latest methods

Over the years, the concept of the world has changed. It is noteworthy that the concept of safety has changed in addition to the system's vision. In the beginning, was the safety-I conception characterized by two assumptions: the decomposition of functions and the bimodal view, that is, the awareness that things can go right and wrong. In this view, man is regarded as a carrier of danger.

However, this does not fit today's world, where systems cannot be decomposed and functions are flexible and variable. This is why the concept of safety-II was introduced.

Here man is not seen negatively anymore but as an entity capable of fixing what is not working. The evaluation of procedures and operator perfor-

mance is based on objective criteria rather than subjective opinions.
Since studying functions in aeronautics, the concept of FRAM based on functional resonance has been developed.[11]
The FRAM method, the Functional Resonance Analysis Method, is a systematic approach to describe how an action takes place. The event is described with functions necessary to carry out the activity. It wants to define the structure of a normal operational mode. It is based on four principles:

1. **Principle of equivalence**: explanation could be used in the major part of cases.
2. **Principle of approximate adjustment**: people adapt their actions to match the conditions.
3. **Principle of emergence**: all the results could correspond to a specific cause.
4. **The Principle of resonance**: functional resonance can be used to describe and explain non-linear interactions and outcomes.

To fully comprehend this model, it is essential to define the term 'function'. A function denotes the necessary steps to achieve a goal. Functions that have already taken place are referred to as upstream functions, while those that follow the current focus are known as downstream functions.
The functions are described in six aspects:

- **Input**: which activates the function. It is the link to upstream functions.
- **Time**: temporal aspects that affect the function.
- **Control**: which supervises or regulates the function.
- **Precondition**: system conditions that must occur to perform the function.
- **Resources**: that which is needed or consumed by the function when it is active, such as energy, manpower, or software.
- **Output**: the result of the function and the link to downstream functions.

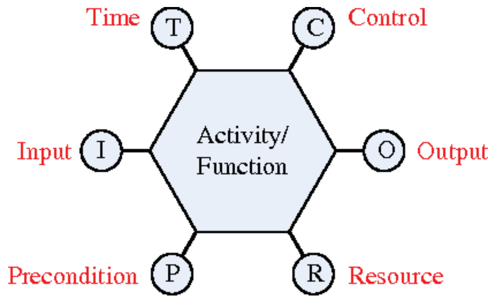


Figure 2.6: Function structure in FRAM

Another method is the STAMP, Systems Theoretic Accident Model and Process, where accidents occur when disturbances, failures, and interactions are not adequately handled by the control system.[23] The control is inadequate. Safety then can be viewed as a control problem, and it is managed by a control structure that operates in a socio-technical system. Its goal is to put constraints on the system.
The qualities of the model are:

- System is described through the level of control and safety is considered like a dynamic control problem.
- The model focuses on the rule of constraints.
- Accidents are seen as resulting from inadequate control or are caused by the interaction between physical systems, humans, and social systems.
- Research why the control does not prevent the accident.

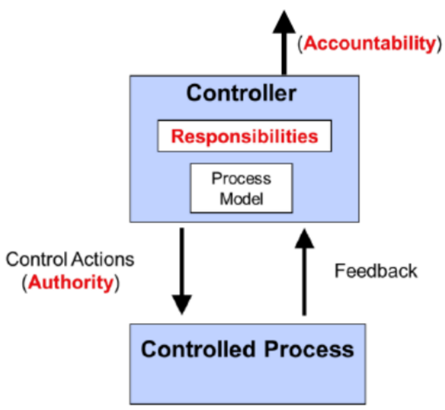


Figure 2.7: Basic building block structure

This model uses a block diagram showing the interactions and connections between the various parts. The image 2.7 shows that the controller requires control action for the controlled process. The controller has responsibility for what concerns the security constraints of the system since he determines the type of control actions. An example of controllers are the FAA for the United States and the EASA for Europe. The feedbacks are reports and accident analysis. They are incorporated into process models(mental processes if we are talking about humans). Knowing all this leads to the conclusion that accidents happen because the controller provides unsafe control actions.
STAMP sets the foundation for two other models such as STPA, System-Theoretic Process Analysis, and CAST, Causal Analysis based on System Theory. The first performs proactive analysis so that we can get to the point of eliminating or controlling the hazard.[20] The second conducts a retrospective analysis that examines incidents that have occurred and identifies the causal factors involved. It is precisely this that we are going to use in the analysis of the cases under consideration.

2.1.3 Peculiarities of some models

To handle the cases under consideration, particularly maintenance errors, it was more advantageous to use updates of previously analyzed models.

Figure 2.8: A-SHELL diagram

A-SHELL model indicates the interaction between various components of the system and the ATM. Similar to the traditional SHELL it comprises four components, Software-Hardware-Liveware-Environment, but Airworthiness was added to link the elements together. It controls planning, management, and control of aircraft maintenance operations. It values maintenance activities based on repair, inspection, and planning.[28]

HFACS-ME results from the evolution of Reason's model, created to conduct a more in-depth analysis of human factors in maintenance activities. The model represents, as the Swiss cheese model, a complex system with a series of barriers riched of holes. If the holes are aligned they will lead to an accident. In the most cases maintenance error are hidden in the system. It is a retrospective method, so it can treat only accidents that already happened. Due to complex cognitive processes, it is so difficult to find casual factors or latent conditions as well.
The particularity of the model lies in the presence of different levels and orders. The first three levels are management, maintainer, and working conditions (latent conditions).[13]
Graphical descriptions of the various methods can be found in Appendix B.

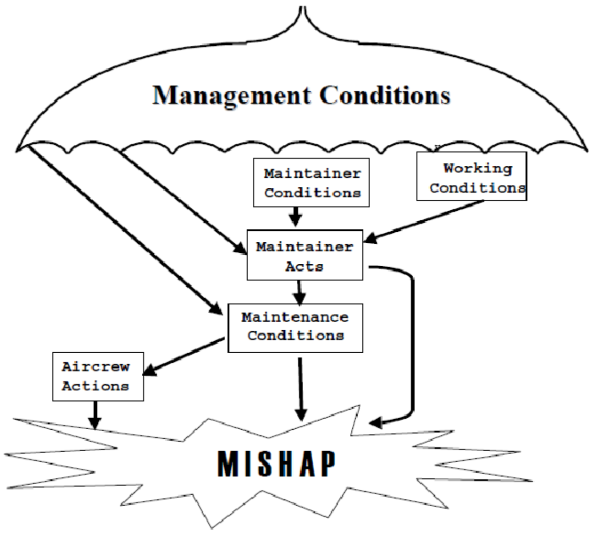


Figure 2.9: HFACS-ME conditions

2.1.4 Case study

The Aloha Airlines accident is treated as an example because it can be analyzed using several techniques. The accident's main cause is a maintenance error, during the inspection phase, that leads to the loss of a fuselage part. This deficiency in the inspections is due to a failure of the maintainers, a failure of the company and the organizational, and control system. The good thing is that a catastrophe was avoided but a person died.

Aloha Airlines Flight 243

On April 28, 1988, at 13.46, a Boeing 737-200, N73711, operated by Aloha Airlines with number flight 243 en route from Hilo to Honolulu experienced an explosive decompression and structural failure. On board, there were 89 passengers and 6 crew members. One flight assistant was moved out during the uncovering and 8 people received serious injuries. So the pilots performed an emergency descent to the Kahului airport.

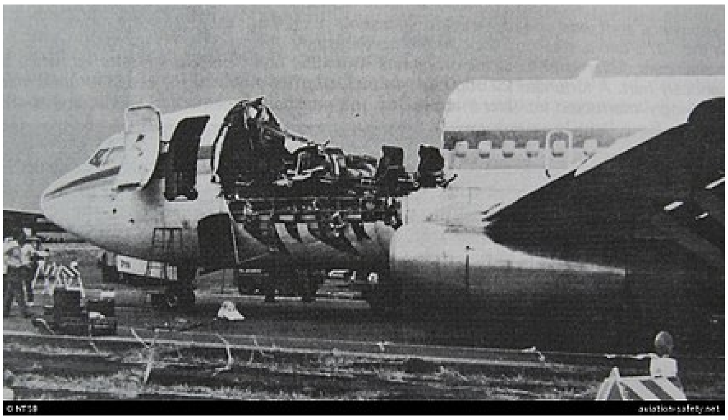


Figure 2.10: Aircraft after the loss of part of the fuselage

The NTSB report was used to carry out the analysis of the incident under review.[25]
The first step concerns the study of the flight history and the maintenance history just to know what happened before and during the accident. This is useful for starting the human factor analysis.
The history analysis was performed through the definition of some sequences. Ten of them were found and then they were analyzed with the SHELL method to identify the interactions between humans and machines. This evaluation allowed HFACS codes to be associated with each sequence, which will be discussed in detail below. The table shows the presence of some latent errors related to lack of supervision between flights (**SP008**) and organizational failures due to deficiencies in Boeing's PMI, Principal Maintenance Inspector,(**OP006**). It is important to recognize the presence of an active failure related to a decision-making error (**AE200**) made from ATC during the emergency phase.

Funcion	SHELL Human Factor	HFACS Nanocodes
F1	L-S Human system interface-Standard operating procedures	/
F2	L-L Worker-Management-Regulatory agency- Inspection	**OP006** INADEQUATE PROGRAM MANAGEMENT/GOVERNANCE **SP008** INEFFECTIVE PRE-MISSION PLANNING
F3	L-S- Human system interface-Standard operating procedures	/
F4	L-E- Internal	**PE108** EXTERNAL FORCE OR OBJECT IMPEDED PERFORMANCE
F5	L- L- Oral Communication-Communication Content	**PE208** COMMUNICATION EQUIPMENT INEFFECTIVE
F6	L- L- Oral Communication-Communication Content	/
F7	L- Individual- Psychological factors- Decision	**AE200** JUDGEMENT AND DECISION MAKING ERRORS
F8	L- L- Oral Communication-Communication Content	/
F9	L- H- Equipment – Workspace-Alerting and Warnings	**PE202** INSTRUMENTATION AND SENSORY FEEDBACK SYSTEMS

Figure 2.11: Comparison between SHELL and HFACS in Aloha Airlines accident

The Flight 243 accident is caused by a maintenance error so it is perfect for solving with the A-SHELL method and the HFACS-ME. Through the first analysis, Boeing was introduced as a latent cause. Noticeable are the deficiencies in NDI inspection training and maintainers' repairing abilities. Here came to light the errors caused by physical and psychological factors. The name of this method also pays attention to the airworthiness part, such as some regulations, service bulletins, and service letters.

- **AD-87-21-08**:Requires careful visual inspection of joints along S-4L.
- **SB 737-531017**: Consider cold sealing to protect against corrosion.
- **SB 737-53A1039**: Temporary repair if cracks are found.
- **737-SL-76-2-A**: Steel engine cables are subject to corrosion.

Meanwhile, when an analysis is performed with HFACS-ME the maintenance conditions are put in the foreground.

To practice the analysis of controllers, it was decided to use the CAST approach. It started with the identification of the main hazard: the part fuselage loss.
The block diagram is formed by the aircraft that is directly controlled by maintainers because they work on it, and joints and rivets control the aircraft enabling the structure to perform at its best. The aircraft gives

L-2 Technical qualification as an AMT	**L-2-3** Knowledge and practical techniques for inspection L-2-4 Knowledge and practical techniques for repairing	Little training and lack of requisites for NDI inspection Many pre-accident repairs were carried out using a patching method.
L-3 Airworthiness requirements on AMT	**L-3-1** Compliance with Hong Kong Airworthiness Requirement (HKAR) 66 Aircraft Maintenance License and approved Maintenance, Repair, and Overhaul (MRO) requirements	Hong Kong Airworthiness Notices Issue 9 Notice 94: (28 June 2019)Personnel Certification for Non-destructive Testing of Aircraft, Engines, Components and Materials.
LS-1 Airworthiness maintenance procedures	**LS-1-2** Implementation of recommended procedures	Inaccurate instructions contained in AD-87-21-08 and Aloha should have followed a maintenance program to detect and repair cracks before they reached a critical level. Complicated and difficult to interpret documents.
LH-1 Operation of equipment	**LH-1-1** Adequate training for equipment operation	There are no requirements for the training of NDI personnel.
LE-1 Airworthiness regulations on working environment	**LE-1-1** Well-lighted	Effect of circadian rhythms on human behavior as maintenance was performed at night. Irregular work and rest schedules.
LE-2 Non-physical factors	**LE-2-1** Excessive pressure for on-time departure	Most of Aloha's maintenance was normally conducted during the night. Mechanics and inspectors were forced to work under pressure. In addition, maintenance personnel were reluctant to keep the aircraft in the hangar longer than necessary.
Liveware-Airworthiness	**L-A-3** Airworthiness regulation on aircraft maintenance procedure development	SB 737-53-1017 AD 87-21-08 SB 737-53A1039 (Allert) SB 737-53A1039 SL 737-SL-76-2-A
Liveware-Airworthiness	**L-A-4** Regulatory Authority Surveillance	The Boeing failed to detect and prevent the use of improper maintenance procedures.

Figure 2.12: A-SHELL analysis

1st oder	**2nd oder**	**3rd oder**	**Specific Failures**
Management Conditions	**Organizational Conditions** **Supervisory Conditions**	**Inadequate Process** **Inappropriate Operations** **Inadequate Supervision** **Supervisory Misconduct**	Task complex/confusion Supervisory improper manning Failure to provide guidance, Failure to provide oversight Known hazards not controlled
Maintainer Conditions	**Maintainer Medical Conditions** **Maintainer Readiness**	**Maintainer Mental State** **Maintainer Physical State** **Maintainer Training/Preparation**	Attention, Life stress, mental fatigue, pressure Circadian rhythm Inadequate knowledge, insufficient job training, inadequate skills
Working Conditions	**Working Environment**	**Lighting/Light**	Night visibility
Maintainer Acts	**Maintainer Errors**	**Attention/Memory Error** **Knowledge/ Rule-Based Error** **Skill/ Techniques Error**	Maintainer fail to recognize condition Maintainer inadequate process knowledge Maintainer poor techniques

Figure 2.13: HFACS-ME analysis

feedback to operators through the appearance of cracks.
Maintainers are controlled by Aloha Airlines company which provides the regulations for their job. The job's supervision is made by Boeing via service bulletins and the PMI, but feedback from PMI did not arrive correctly because it was too overworked.

The analysis concludes with recommendations. In addition to those included in the NTSB report, three more are suggested: one regarding the operation of Aloha Airlines and two regarding the ATC job.

- Improving pilot training in emergency cases where the integrity of the aircraft is put at risk.
- Improve the training of ATC operators in emergencies so that, through their work, they try to help the aircraft as best they can.
- Improving operators' ability to read accident scenarios (ambulance case).

To facilitate comprehension of the causes of the accident and identify areas for improvement, it is recommended to use the FRAM method to analyze

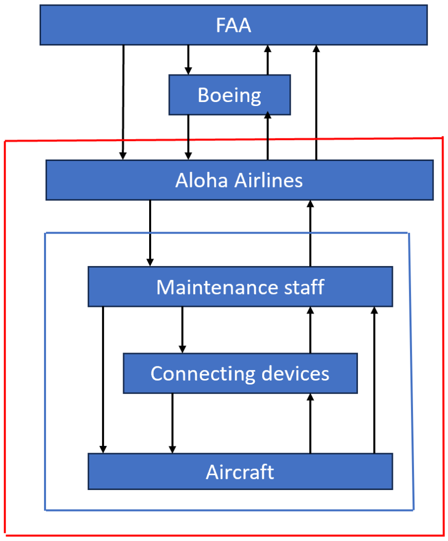


Figure 2.14: Block diagram of Aloha Airlines accident

the pilots' actions and the potential outcomes if proper procedures had been followed. This approach allows for the identification of relevant variables that contributed to the accident.

Work carried out following procedures

This model is formed by five functions that describe the activities to be performed by the operator involved. The foreground functions are conducted by maintainers and the company, the background functions are carried out by pilots and ATC members.
The first function under analysis is related to the work of the FAA (**FAA controls the operations of companies**) which is responsible for carrying out the necessary inspections and defining regulations. Its output represents the input of three functions, two of which are considered foreground functions, which are fundamental to the process, attributed to Boeing (**Boeing executes complete fatigue test on 737**) and to Aloha Airlines (**Aloha Airlines provides maintenance training**). The other one is a background function related to pilots' operations (**Crew follow the rules**).
The Aloha and Boeing's functions are controlled by the FAA and their success allows for safe flying.
The scheme is represented in figure 2.15.

Work carried out by the pilots

This model differs from the previous one because the performance of ac-

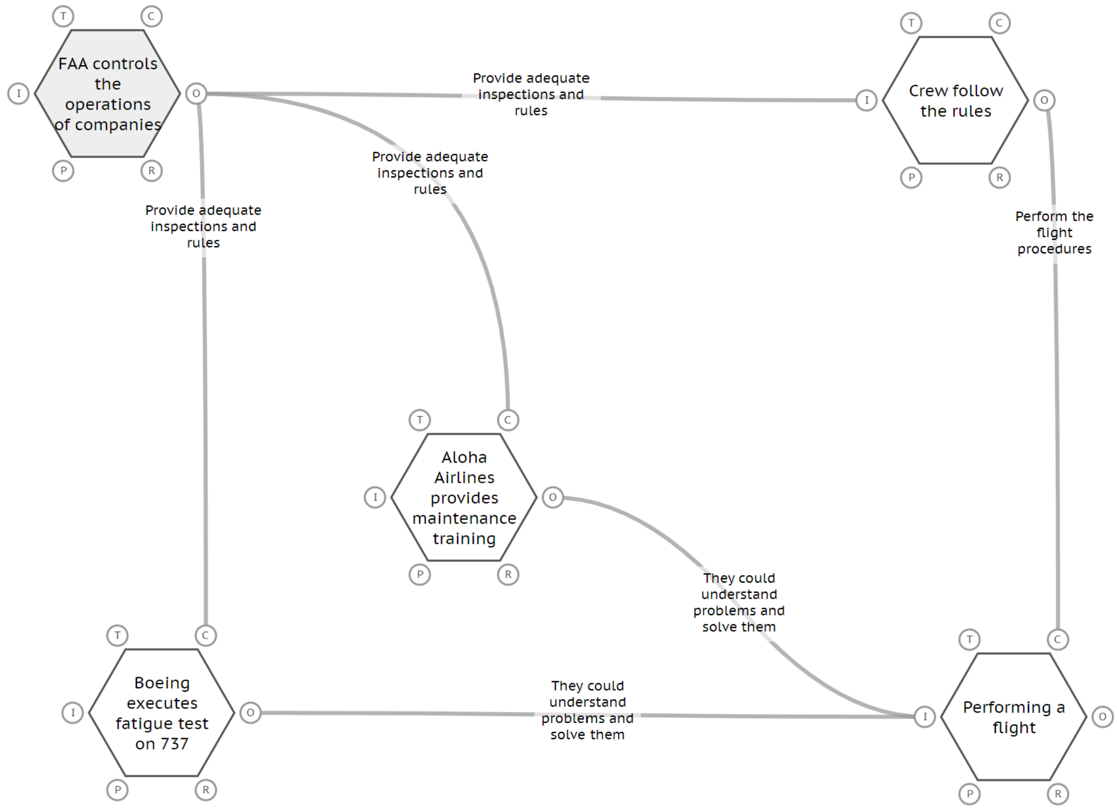


Figure 2.15: Work carried out following procedures

tivities changes.

The first variability is present in the function (**FAA controls the operations of companies**) which, independently of the ADs issued and the warnings to companies, did not carry out effective supervision. The variability cascaded down to Boeing, which did not carry out fatigue tests and corrosion checks, and to Aloha Airlines, which did not introduce deep maintenance training.

Since fundamental steps were missing, the flight could not be carried out.

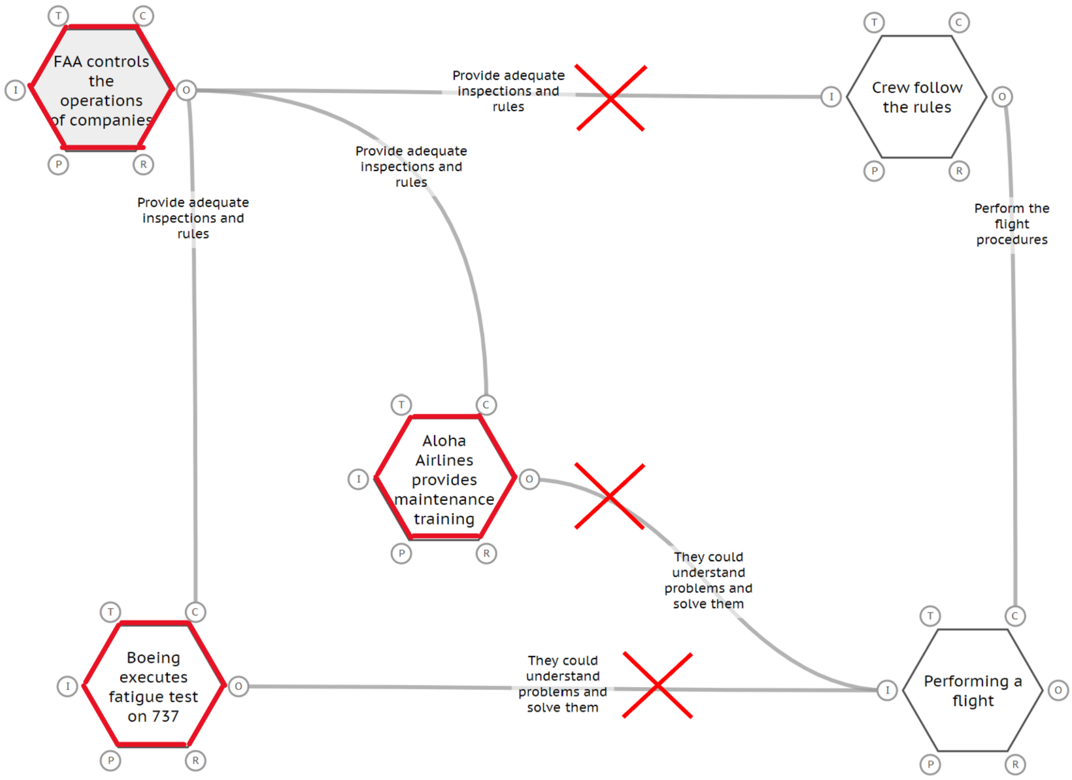


Figure 2.16: Work carried out by the pilots

Variability and comparison with HFACS

The variabilities are studied based on their relationship with other functions.

Funcion	Output		Downstream Funcion	Time	Effect	Precision	Effect		HFACS
FAA controls the operations of companies	Provide adequate inspections and rules	C	Aloha Airlines provides maintenance training	Omission	Alternative control is sought, if possible	Imprecise	Delays and trade-off with regard to accuracy and precision	V+	OP003 PE208 OR008 SD001
		C	Boeing completes fatigue test on 737						
Boeing executes complete fatigue test on 737	They could understand problems and solve them	I	Performing a flight	Omission	The function is not performed or is significantly delayed	Imprecise	Loss of accuracy	V+	SP010 SP008 OT000
Aloha Airlines provides maintenance training	They could understand problems and solve them	I	Performing a flight	Too late	Delays that can lead to increase the use of shortcuts	Imprecise	Loss of time	V+	AE200 AD000 OP006

Figure 2.17: Analysis of FRAM functions

The function that started it all was (**Boeing executes complete fatigue test on 737**) analyzed as a failure of work because the work that had to be done was not done in the best possible way. The functions are better described in the Appendix C.
The FRAM analysis led to the discovery of a violation described with the

code (**AD000**) that is an active failure.

	HFACS	FRAM
ORGANIZATIONAL INFLUENCES	**OP006** INADEQUATE PROGRAM MANAGEMENT/GOVERNANCE	**OP003** PROVIDED UNCLEAR, IMPRACTICAL, OR INADEQUATE POLICY, PROCEDURAL GUIDANCE OR PUBLICATION **OP006** INADEQUATE PROGRAM MANAGEMENT/GOVERNANCE **0R008** FAILURE TO PROVIDE ADEQUATE INFORMATION RESOURCES **OT000** TRAINING PROGRAMME ISSUES
SUPERVISION / LEADERSHIP	**SP008** INEFFECTIVE PRE-MISSION PLANNING	**SD001** FAILURE TO ENFORCE PUBLISHED RULES/GUIDANCE **SP008** INEFFECTIVE PRE-MISSION PLANNING **SP010** UNIT FAILURE TO PROVIDE SUFFICIENT MANNING/STAFFING
PRECONDITIONS	**PE202** INSTRUMENTATION AND SENSORY FEEDBACK SYSTEMS **PE208** COMMUNICATION EQUIPMENT INEFFECTIVE **PE108** EXTERNAL FORCE OR OBJECT IMPEDED PERFORMANCE	**PE208** COMMUNICATION EQUIPMENT INEFFECTIVE
UNSAFE ACTS	**AE200** JUDGEMENT AND DECISION MAKING ERRORS	**AE200** JUDGEMENT AND DECISION MAKING ERRORS **AD000** KNOWN DEVIATIONS

Figure 2.18: Comparison between HFACS and FRAM analysis

The comparison of the human factors, shown in figure 2.18, revealed similarities and mismatches. It should be remembered that the HFACS analysis was carried out in connection with the SHELL analysis based on the accident history while FRAM is based on the analysis of what should have been done and what was done. It is for this study that FRAM introduces the presence of a violation in the accident analysis. The preconditions in HFACS are mostly related to the environment. The unsafe supervision is related to pilots' jobs meanwhile in FRAM it is extended to Boeing's operations and FAA controls. A big point in favor of FRAM was finding failures in the control structure.

- **OP003** PROVIDED UNCLEAR, IMPRACTICAL, OR INADEQUATE POLICY, PROCEDURAL GUIDANCE OR PUBLICATION
- **OR008** FAILURE TO PROVIDE ADEQUATE INFORMATION RESOURCES
- **OT000** TRAINING PROGRAMME ISSUES

Chapter 3

A new model

	SHELL	HFACS	Swiss Cheese	FRAM	CAST
How it works	Concern technical and human aspects. Evaluate how human factors interact with system components.	Human error theory focuses on analyzing human errors and the causes leading to accidents.	Accidents happen when the holes in the barriers are lined up. It is a graphical presentation of security deficiencies caused by human error.	System complex theory based on interactions of functions in the system and analysis of what is going well. Useful to evaluate safety and system performance.	Systemic approach and focus on interactions between system components and events, to understand the causal factors that lead to accidents. Analyzes what should be avoided then provides recommendations.
Limits	Does not study interfaces outside of human factors.	Does not lead to predicting and eliminating causes leading to the accident.	Errors are based on a defined context. Limited to an accident trajectory.	Interpretation of maps can be subjective and complicated. Focusing on functions and their interactions may not find all failures.	Difficulty in finding causal factors. The results, depend on the system under analysis, and may not be generalizable.

Figure 3.1: Graphical summary of model features

The accident analysis above has permitted a better understanding of the use of models evaluating all the advantages and disadvantages of using one method rather than another.
It was concluded that there is no right or wrong, everything depends on the framework.
However, by working synergistically with all methods, a solution could be created that takes advantage of the potential of each of them.
It is for this reason that this research has produced a model.

3.1 Hybrid model

The goal of this method is to provide an exhaustive analysis during the investigation phases.
It is called hybrid because it is characterized by aspects of all previously mentioned methods.
The model pays attention to the interaction of human factors in accidents and it provides some possible recommendations to improve, mitigate, and

solve some accident causes that could lead to an accident.
This analysis is retrospective because the study is carried out post-accident with the aim of finding the deficiencies of the system characterized by human-machine interaction. It is possible to find the active and latent errors classified through the interaction between SHELL and HFACS.
The scheme of the performance of the pilot is compared with the scheme of the correct performance of the action and thanks to this it is easier to uncover latent errors in the system.
The method was not created to assign blame but to find what needs to be done to prevent accidents.
It is structured as follows:

- Data collection at the accident site. Acquisition of witness statements, radar traces, ground-to-ground radio communications, information about pilot training and the pilot's life, and recovery of the flight recorder.

- Development of the main concept of root causes by using a fishbone diagram where it is possible to analyze the human, machine, environment, and software contributions. These inputs are visible in the collection of data acquired by the flight recorder.
  In this first part, possible issues that potentially led to the accident are evaluated. So in the next steps, a lot of attention is paid to this and what these factors produce.

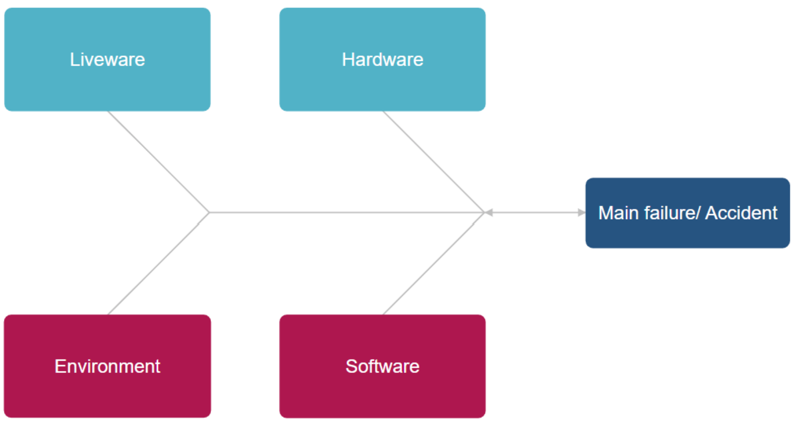


Figure 3.2: Fishbone diagram first implementation

- A systems perspective is developed to enable the evaluation of humans and their interactions with their environment. Mistakes are rarely made by a single person. Therefore, the performance of all operators should be assessed. In this way, it is possible to find the active causes of the accident under investigation.

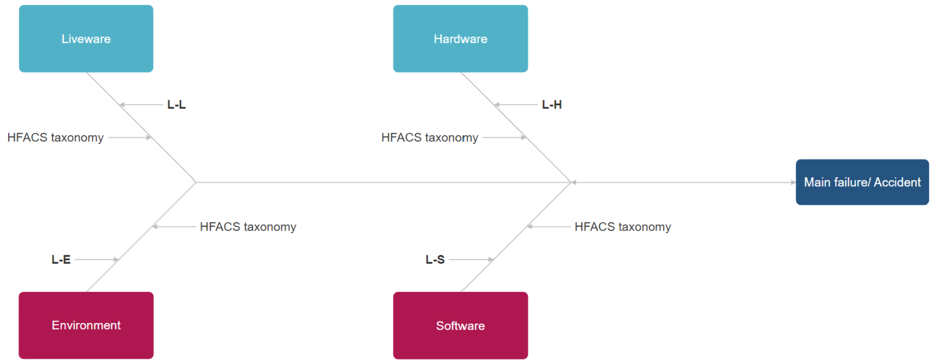
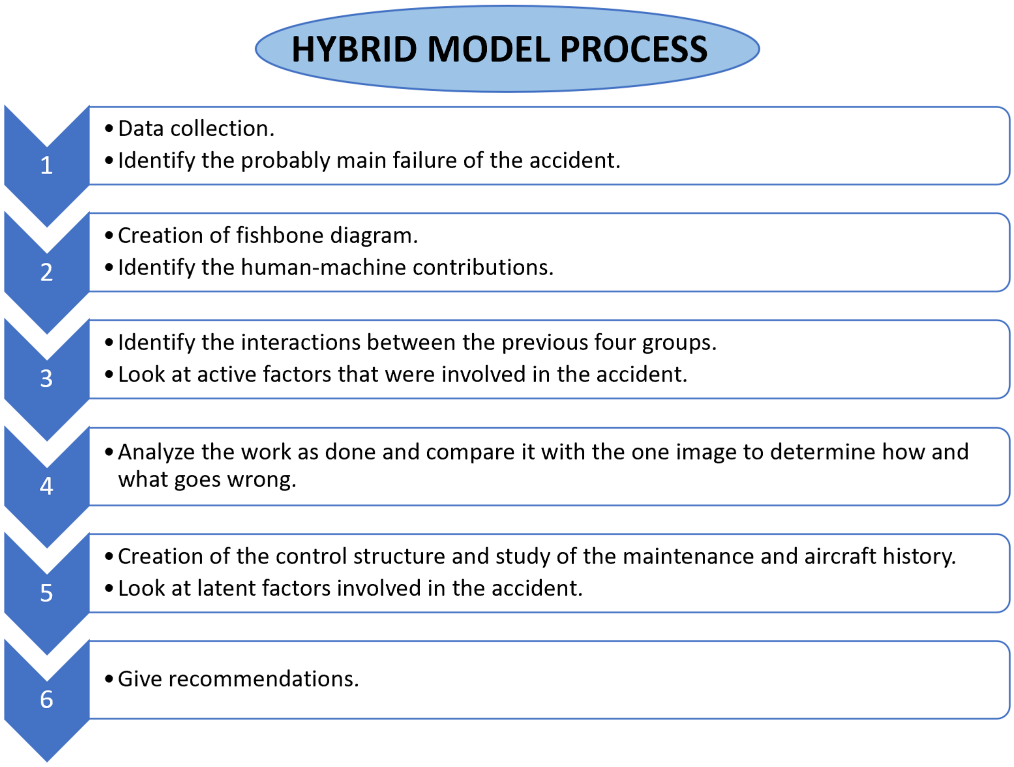


Figure 3.3: Fishbone diagram implementation with interaction between parts

- After understanding how the accident happened, it is necessary to compare the correct dynamics of the procedures with the one performed by pilots resulting in an accident. Using a diagram, it is easy to visualize the possible causes that, in conjunction with the active causes, potentially led to the accident, and therefore their analysis is in-depth.
- It is useful to go back to the maintenance history of the aircraft. A block diagram was created to aid in the backward analysis of those who may have contributed to the accident. After this, it will be possible to define all the latent causes that contribute to the accident.
- Recommendations are made to prevent certain mistakes from being repeated.


HYBRID MODEL PROCESS
1
• Data collection.
• Identify the probably main failure of the accident.
2
• Creation of fishbone diagram.
• Identify the human-machine contributions.
3
• Identify the interactions between the previous four groups.
• Look at active factors that were involved in the accident.
4
• Analyze the work as done and compare it with the one image to determine how and what goes wrong.
5
• Creation of the control structure and study of the maintenance and aircraft history.
• Look at latent factors involved in the accident.
6
• Give recommendations.

Chapter 4

Application of hybrid method

Three examples are used to demonstrate the hybrid method. These are three accidents characterized by the predominant presence of the human factor visible in the decisions of pilots in the cockpit, in the work of maintainers, and in the aircraft design program.
The accidents treated follow the order of the main causal factors listed above.

- Air France flight 447 from Rio de Janeiro to Paris.
- Flight Tuniter 1153 from Bari to Djerba.
- Lion Air 610 from Tangerang to Pangkal Pinang, in Indonesia.

4.1 Case study 1: AF447

The accident of an Airbus A330-200 occurred on 31 May 2009 from Rio de Janeiro Galeão airport to Paris Charles de Gaulle airport. [9] The flight was in contact with the Atlantico control center on the INTOL-TASIL route at FL350. During the flight, there was an obstruction of the Pitot probes due to ice crystals. This led to autopilot disconnection and a problem with the indicator of airspeed. The aircraft stalled and crashed into the sea at 2:14 am.
The plane had 228 occupants: all died in the crash.

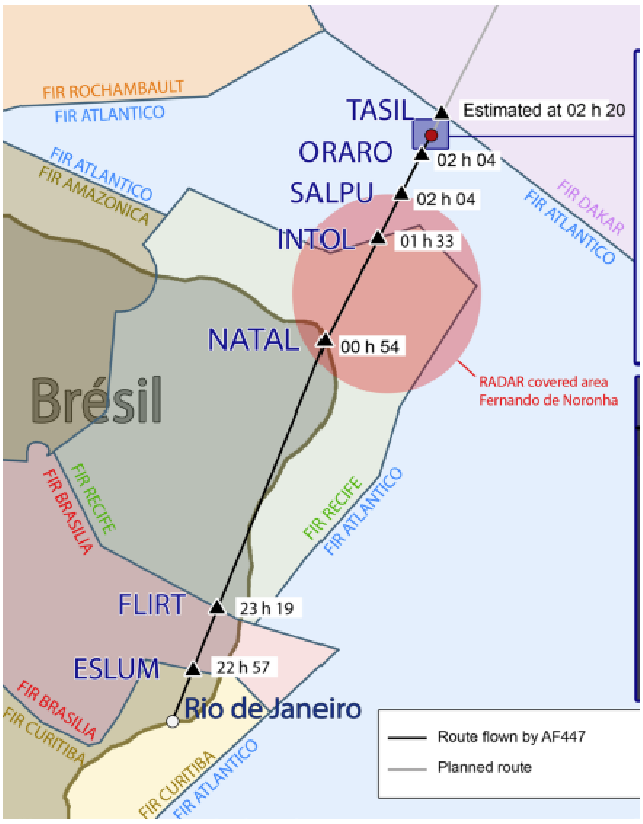


Figure 4.1: Case 1: Waypoints

22h 00	Departure planned
22 h 10	The crew was cleared to start up engines and leave the stand
22h 29	Take off
00 h 30	The crew had received information from the OCC about the presence of a convective zone between SALPU and TASIL
1h 35	Arrive at INTOL point and change to HF communication
1h 35	A SELCAL test was successfully carried out, but attempts to establish an ADS-C connection with DAKAR Oceanic failed
1h 40	The crew noticed "a thing straight ahead" (meteorological issue)
1h 45	The airplane, before SALPU point, entered a turbulence zone
1 h 52	The turbulence stopped
2h 00	Captain was leaving his seat. The less experienced pilot takes the lead
2h 06	The PF called the cabin crew
2h 06	Passengers requested to sit down
2h 08	The engine de-icing was turned on and the PNF proposed to go to the left
2h 10	Iced pitot tubes
2h 10min 05	The autopilot disconnected, stall warning and the system fly-by-wire passed from normal law to alternate law
2h 10min 16	Loss of speed indication
2h 10min 25	The PNF read out the ECAM messages in a disorganized manner
2h 10min 36	The speed displayed on the left side became valid again and the ISIS speed was still erroneous
2h 10min 50	The PNF called the captain several times
2h 10min 51	The stall warning was triggered again because the PF continued to make nose-up inputs. The speed indicators were working again
2h 11min 37	The PNF took control for 30 seconds and the captain returned
2h 12	Problems on the electronic artificial horizon
2h 13	The two pilots gave simultaneous but reversed commands
2h 14	The GPSW warning rang

Figure 4.2: Case 1: History of flight

The aircraft disappeared in an unstable region where trade winds from both hemispheres generate powerful storms. As the figure 4.1 shown the aircraft disappeared near the TASIL waypoint.
Many questions arise. What were the conditions outside the aircraft? Was there lightning?
The remains of the aircraft showed that the brakes were static, and no damage was caused by wear. The plane hit the water in one piece so turbulence was not to blame for the fall.
Analyzing the CVR and FDR data, it was discovered that the Pitot probes froze during the turbulence crossing. With this data, it is possible to delineate the true history of the flight on 31 May. It is also possible to define the main cause which is the aerodynamic stall.

As mentioned above turbulence caused the icing of the Pitot probes. This led to the incorrect speed indication and the inactivation of the autopilot. At these stages, there was a lot of noise in the cockpit caused by alarms that stressed the pilots and produced confusion. The two pilots reacted to

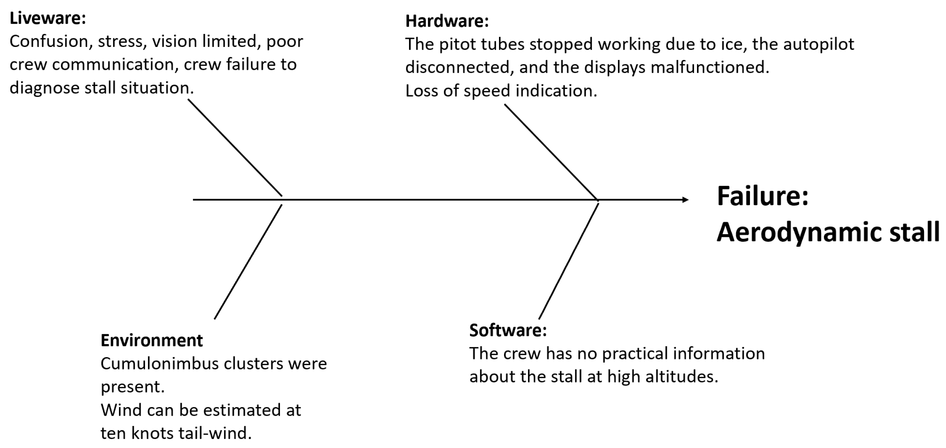


Figure 4.3: Case 1: Fishbone diagram

the problem in different ways without actually realizing it because communication inside the cockpit was poor.
With this preliminary study of interactions provided by the data collected from the recordings, pilot training, and at the event site, it was possible to define the active errors in the accident. The HFACS nano-codes show the presence of two unsafe acts, **AE108** and **AE200**, the first one is related to the performance of the PNF that read out the ECAM message in a disorganized mode, and the second one is referred to the pilot's perceptions because they did not react correctly to the problem. But what stands out most is the strong presence of preconditions because there must be one to accompany every unsafe act. The preconditions have influenced the behavior of humans and have led to unsafe acts.

- **PE206** WORKSPACE LIMITATIONS AFFECTED PERFORMANCE
- **PT101** UNTRAINED OPERATOR/ WORKER
- **PT104** LACK OF PROFICIENCY/EXPERIENCE
- **PP101** INEFFECTIVE TEAM RESOURCE MANAGEMENT

It is crucial to develop a study on these preconditions because it is better to know more about Pitot probes and the design of the Airbus cockpit since the pilot did not receive feedback on their joystick concerning what the other pilot was doing.
Furthermore, it is necessary to investigate why there were gaps in the

experience regarding aircraft stall procedures at high altitudes.

Liveware	L-individual-Psychological factors- Perceptions- Reaction time to make an appropriate action L-individual-Psychological factors- Disorientation-Situation Awareness L-individual-Psychological factors- Information Processing-Decision Making Coordination L-Individual-Mental/ Emotional state L-individual- Training- Emergency procedures L-individual- Knowledge-Competence
Liveware-Liveware	L- L- Oral Communication- Crew interaction L-L- Worker- Management-Training
Liveware-Hardware	L- H – Workspace-Alerting and Warnings L- H- Equipment – Instrument-controls design
Liveware-Software	L-S-Written information-Standard operating procedures/ Task saturation
Liveware-Environment	L-E-External -Weather visibility/Turbulence L-E-External – Other factors-Water Obstacle

Figure 4.4: Case 1: The interactions analyzed through SHELL

Organizational Influence	/
Supervision/Leadership	/
Preconditions	**PE101** ENVIRONMENTAL CONDITIONS AFFECTED VISION **PE108** EXTERNAL FORCE OR OBJECT IMPEDED PERFORMANCE **PE202** INSTRUMENTATION AND SENSORY FEEDBACK SYSTEMS **PE206** WORKSPACE LIMITATIONS AFFECTED PERFORMANCE **PE208** COMMUNICATION EQUIPMENT INEFFECTIVE **PC103** TASK SATURATION **PC104** CONFUSION **PC203** LIFE STRESSORS/EMOTIONAL STATE **PP101** INEFFECTIVE TEAM RESOURCE MANAGEMENT **PT101** UNTRAINED OPERATOR/ WORKER **PT104** LACK OF PROFICIENCY/EXPERIENCE
Unsafe acts	**AE108** MISINTERPRETED/ MISREAD INSTRUMENT **AE200** JUDGEMENT AND DECISION MAKING ERRORS

Figure 4.5: Case 1: The history of flight analyzed through HFACS

First of all, it is essential to define a Pitot probe. It is a pressure-sensitive probe used to determine Mach, the air velocity, altitude, and its trend. In the case of the presence of ice, there is a temporary and reversible deterioration of the total pressure measurement. According to the flight conditions, if the concentration of crystals is greater than the capacity for de-icing of the heating element and evacuation by the purge holes, the crystals accumulate in large numbers in the probe tube. As a result, a physical barrier is created inside the probe that will disturb the measurement of total pressure. Experience and follow-up of these phenomena in very severe conditions show that this loss of function is of limited duration, in general around one or two minutes.

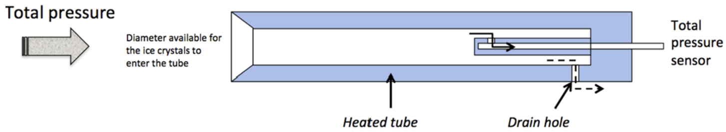


Figure 4.6: Case 1: Pitot probe structure

Therefore, in one minute the probes were de-icing and the speed indicator was working properly again. In this case, it would have been necessary to continue providing power to the aircraft to move ahead and maintain the same direction to enable flight stability. But this was not the case. Whoever was piloting at the time pulled back the cloche and raised the nose. This caused the aircraft to incline and slow down. Stall alarms went off in the cabin and the wings began to lose lift. The aircraft starts to go down as the pilot continues to lift the nose.

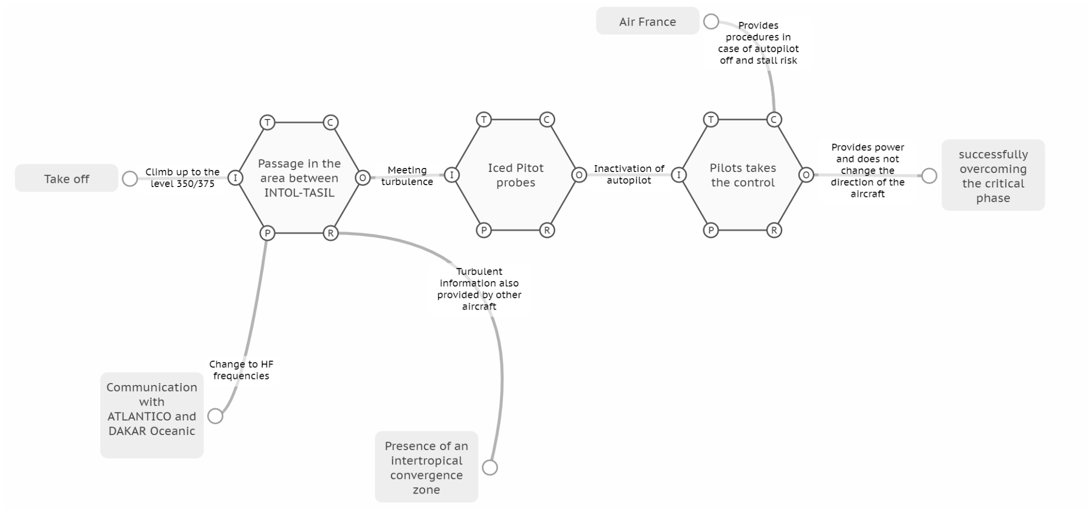


Figure 4.7: Case 1: Work carried out following procedures

The analysis presented in the figure 4.8 shows that in addition to the failure of the pilots' work, there was another one resulting from the actions of Air France. Following the process of the hybrid model, it is appropriate to define the control structure to analyze everything in the background. The analysis of functions is presented in Appendix D.1.

•

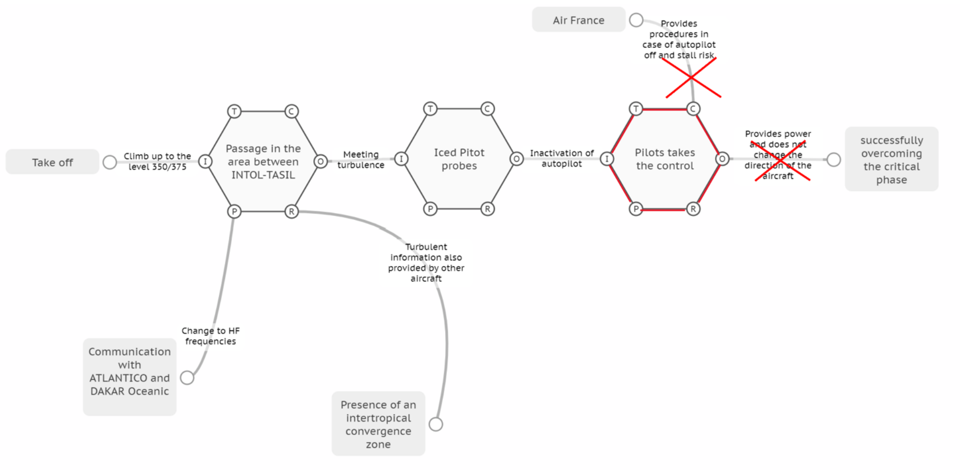


Figure 4.8: Case 1: Work carried out by the pilots

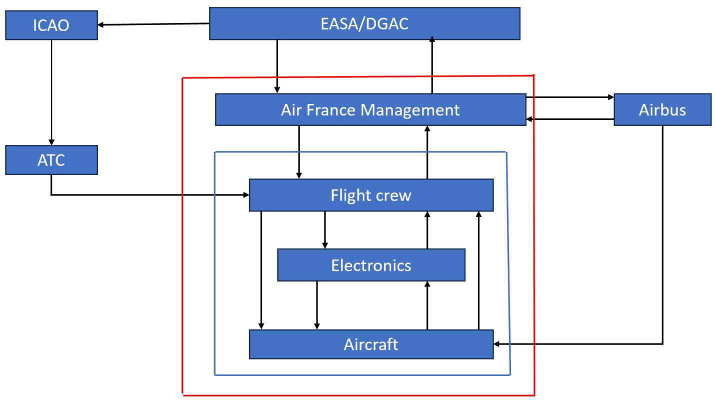


Figure 4.9: Case 1: Block diagram

Airbus and Air France are supervised by EASA and DGAC France, respectively, in accordance with regulations. The operation of ATC is overseen by ICAO. Air France provides information to Airbus which also receives details directly from the aircraft through automatic messages.
The aircraft is controlled by pilots through electronic means such as computers, instruments, and autopilot. Feedback is provided to the pilots through vibrations. Air France controls the pilots, while Airbus designs the aircraft and provides policies and recommended practices.
So two latent errors stand out:

- Delays in replacing pitot probes.
- Failure to train on high altitude stall procedures.

Summarize this by comparing the results with the first analysis and the last one allows us to notice organizational failures, like **OR005** due to delays in replacing pitot probes, and **SI003** and **SI007** regarding pilots training and the failure to solve dangerous situations caused by alarms and equipment.

	First Analysis	Last Analysis
Organizational Influence	/	**OR005** FAILURE TO REMOVE INADEQUATE/WORN-OUT EQUIPMENT IN A TIMELY MANNER
Supervision/Leadership	/	**SI003** FAILED TO PROVIDE EFFECTIVE TRAINING **SI007** FAILED TO IDENTIFY OR CORRECT HAZARDOUS PRACTICES, CONDITIONS, OR GUIDANCE
Preconditions	**PE101** ENVIRONMENTAL CONDITIONS AFFECTED VISION **PE108** EXTERNAL FORCE OR OBJECT IMPEDED PERFORMANCE **PE202** INSTRUMENTATION AND SENSORY FEEDBACK SYSTEMS **PE206** WORKSPACE LIMITATIONS AFFECTED PERFORMANCE **PE208** COMMUNICATION EQUIPMENT INEFFECTIVE **PC103** TASK SATURATION **PC104** CONFUSION **PC203** LIFE STRESSORS/EMOTIONAL STATE **PP101** INEFFECTIVE TEAM RESOURCE MANAGEMENT **PT101** UNTRAINED OPERATOR/ WORKER **PT104** LACK OF PROFICIENCY/EXPERIENCE	**PE101** ENVIRONMENTAL CONDITIONS AFFECTED VISION **PE108** EXTERNAL FORCE OR OBJECT IMPEDED PERFORMANCE **PE202** INSTRUMENTATION AND SENSORY FEEDBACK SYSTEMS **PE206** WORKSPACE LIMITATIONS AFFECTED PERFORMANCE **PE208** COMMUNICATION EQUIPMENT INEFFECTIVE **PC103** TASK SATURATION **PC104** CONFUSION **PC203** LIFE STRESSORS/EMOTIONAL STATE **PP101** INEFFECTIVE TEAM RESOURCE MANAGEMENT **PT101** UNTRAINED OPERATOR/ WORKER **PT104** LACK OF PROFICIENCY/EXPERIENCE
Unsafe acts	**AE108** MISINTERPRETED/ MISREAD INSTRUMENT **AE200** JUDGEMENT AND DECISION MAKING ERRORS	**AE108** MISINTERPRETED/ MISREAD INSTRUMENT **AE200** JUDGEMENT AND DECISION MAKING ERRORS

Figure 4.10: Case 1: Final comparison of two analyses

Finally, here are some recommendations that could be helpful in the future.
Recommendations are made mainly to improve the work of pilots and organizational policies of Airbus.

- Change the stall warning so that the activation is continuous when the aircraft is in a stall.

- Review the feedback given by the cloche and redesign the system to provide accurate feedback.
- Improve pilot training on high-altitude stall procedures, adverse weather, icy probes, and defining roles inside the cockpit in emergencies.
- Review the resting time of pilots.
- In the case of a pilot leaving the cockpit provide a special emergency signal to recall the crew member to the cockpit.

4.2 Case study 2: Flight Tuniter 1153

On August 6, 2005, an accident involved an ATR72-202 aircraft from Bari to Djerba, Tunisia.[8] The aircraft is ditched into the sea in front of the coast of Palermo following the failure of both engines. During the flight, there was right engine shut off so the crew decided to divert to Palermo's airport. They did not arrive at the land.
On board, there were 39 people, 35 passengers and 4 crew members. On impact with the surface of the sea, the aircraft broke into three parts and 16 people died.

Figure 4.11: Case 2: How the aircraft broke down

The flight data record shows that the main failure of flight TUI 1153 was the engine's shutdown. The testimony of pilots reported that the low fuel pressure signal was also present in the cockpit. Why did this happen? Why did the engines stop working? Through the acquired data, it was possible to define the flight history and analyze it. The history of flight and more details are presented in D.2

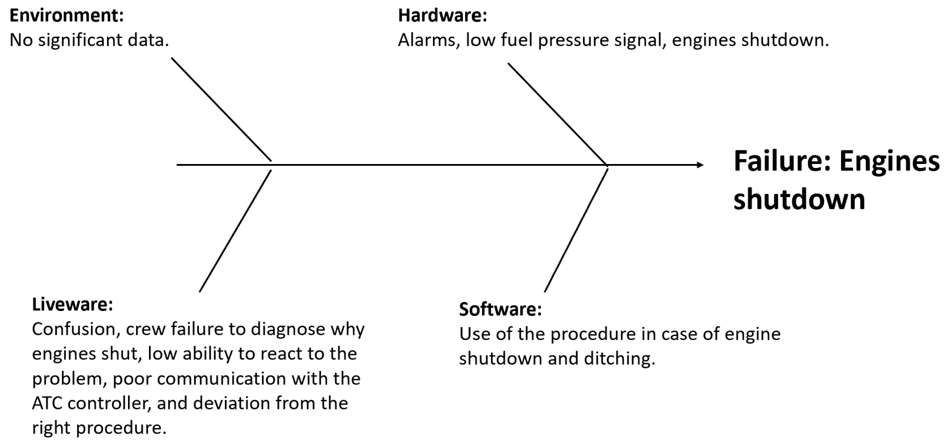


Figure 4.12: Case 2: Fishbone diagram

The aircraft operated two flights, one from Tunis to Bari and one from Bari to Djerba. The last one was not completed.
Preliminary analysis shows that there is a rich presence of human-human interaction related to oral communication through crew members and with the ATC controller and it is clear that the passengers did not follow the emergency procedure on inflating lifejackets. There are many psychological factors associated with situational awareness, mental state and appropriate decisions to be made.
By using HFACS codes, attention is focused on a serious violation committed by the captain and the ATC controller in Bari. **AD001** and **SD002** refer to the decision, against protocol, to fly without the fuel slip. Nobody asked why the document was missing. In addition to classic errors related to ditching decisions, delays in declaring an emergency state, and sloppy procedures, there is the **AE104** code which refers to inadequate control of the aircraft, in particular the understanding of the reason for the engines shutting down.
Preconditions are related to the presence of water seen as an obstacle to landing and the inadequate division of duty in the cockpit since the captain performs the same task as the co-pilot, attempting to start the engines.

Liveware	L-Individual- Psychological factors- Perceptions-Disorientation- Situational awareness L-Individual- Psychological factors- Perceptions-Reaction time- to detect/ To make an appropriate decision L-Individual- Psychological factors- Information Processing- Judgement L-Individual- Psychological factors- Knowledge L-Individual- Psychological factors-Mental/Emotional state
Liveware-Liveware	L-L – Oral Communication- Communication Content L-L- Crew Interactions- Resource Management L-L- Passengers- Procedures
Liveware-Hardware	L-H- Equipment- Workspace- Alerting and Warnings
Liveware-Software	L-S- Human System Interface- Standard Operating Procedures
Liveware-Environment	L-E- External- Other factors- Water obstacle

Figure 4.13: Case 2: The interactions analyzed through SHELL

Organizational influence	/
Supervision/Leadership	**SD002** ALLOWED UNWRITTEN PRACTICES TO BECOME STANDARD
Preconditions	**PE108** EXTERNAL FORCE OR OBJECT IMPEDED PERFORMANCE **PE202** INSTRUMENTATION AND WARNING SYSTEM ISSUES **PE205** AUTOMATED SYSTEM CREATED A HAZARDOUS CONDITION **PE208** COMMUNICATION EQUIPMENT INEFFECTIVE **PP101** INEFFECTIVE TEAM RESOURCE MANAGEMENT **PC104** CONFUSION **PC203** EMOTIONAL STATE
Unsafe acts	**AE100** PERFORMANCE/SKILL-BASED ERRORS **AE104** UNDER CONTROLLED AIRCRAFT **AE200** JUDGEMENT AND DECISION MAKING ERRORS **AD001** PERFORMED KNOWN DEVIATION

Figure 4.14: Case 2: The history of flight analyzed through HFACS

But could the pilots have reached Palermo without the two active engines? This is the question that it is necessary to answer to develop the analysis. First, it is essential to explain the correct procedure after the discovery of these problems.

When the glide stars, it is useful to flag down the thrusters to reduce

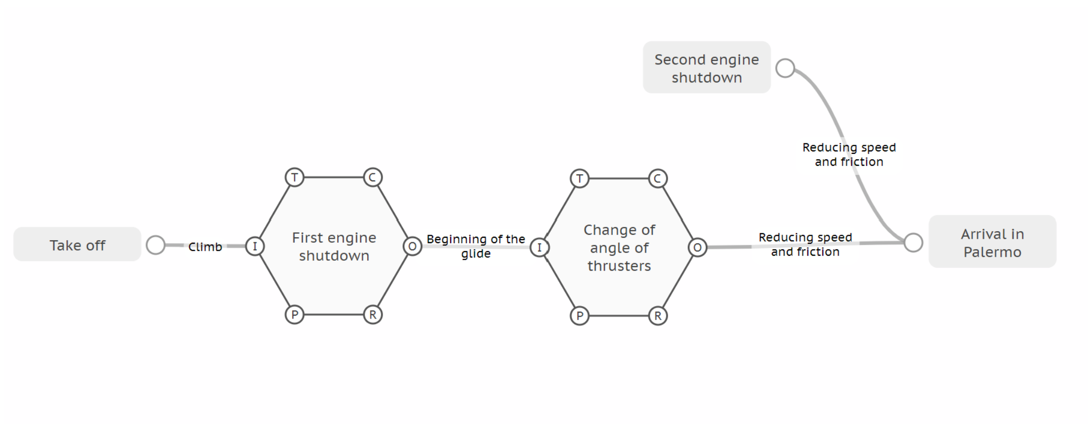


Figure 4.15: Case 2: Work carried out following procedures

friction, thereby reducing speed. In this case, the pilot did not proceed in this way so there was a concatenation of events that led to a fatal ditching. The ideal speed for a glide for the ATR72 is 254 km/h but here the speed was 88 km/h faster. With careful analysis and knowledge of the aircraft in use, it would have been possible to arrive at Palermo, 48 nautical miles away (approx. 88 km), because the plane could glide for 112 km, 5km every 300 meters of descent. It is also important to consider the psychological factors given by the risk of life at that time.

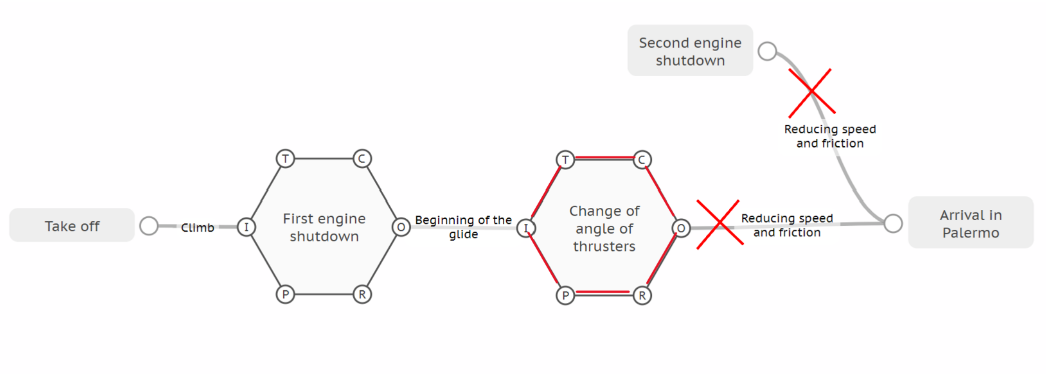


Figure 4.16: Case 2: Work carried out by pilots

The image 4.16 raises to another question: Why were the engines shut down?
To answer it is fundamental to build a control structure of what there is behind pilots and ATC controllers.

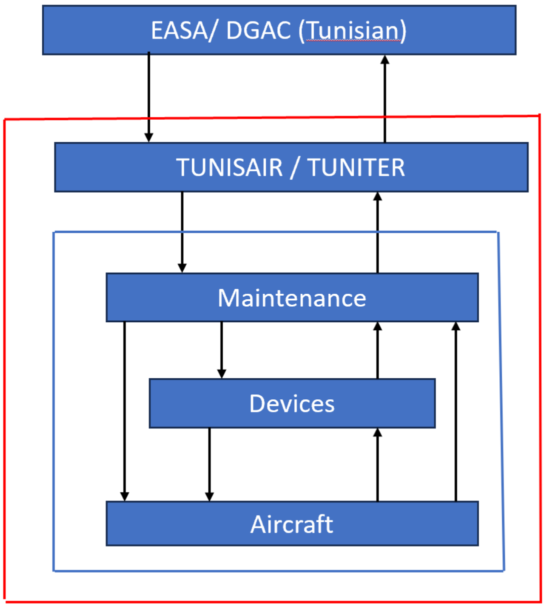
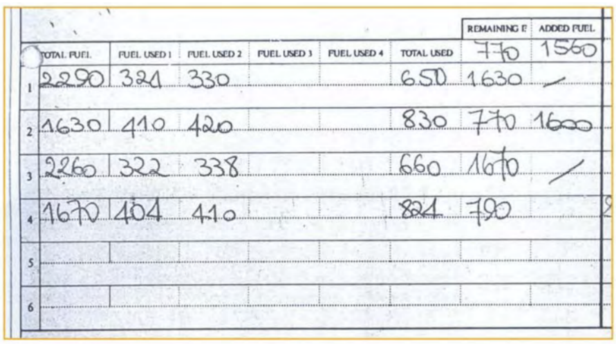


Figure 4.17: Case 2: Block diagram

EASA and DGAC (Tunisian) supervise Tunisair using regulations.
The aircraft is checked directly by maintenance. The aircraft's performance is directly controlled by the operation of its devices.
So to find latent failures is important to analyze what happened during the maintenance that occurred on August 5 due to negative feedback from

the crew that had used the aircraft that day.
Maintenance was done overnight in connection with a shift change.
The maintainer searched for the required FQI in the online catalog but the search produced no results because the parts were in stock and had not been added to the catalog. The technician extended the search by finding an FQI with P/N 748-465-5AB applicable on ATR72 and ATR42 according to the information on the online platform. The information was wrong. Since it was not in stock, he looked for another FQI compatible with it. He found a FQI. Another problem came up because due to negligence the change technician did not carry out the check test.
An ATR-42 indicator is physically almost identical to an ATR-72 indicator but they are not interchangeable. The ATR-42 has smaller fuel tanks than the ATR-72 and consequently, the two types of FQIs use different algorithms to calculate the total amount of fuel. When an ATR-42 FQI was installed on an ATR-72, it applied the wrong formulas to the source data and produced an incorrect reading. It indicated 1,800 kilograms of fuel when the tanks were empty.



	TOTAL FUEL	FUEL USED 1	FUEL USED 2	FUEL USED 3	FUEL USED 4	TOTAL USED	REMAINING F	ADDED FUEL
							770	1560
1	2290	324	330			650	1630	
2	1630	410	420			830	770	1600
3	2260	322	338			660	1670	
4	1670	404	410			824	790	
5								
6								

Figure 4.18: Case 2: Page showing refueling operations

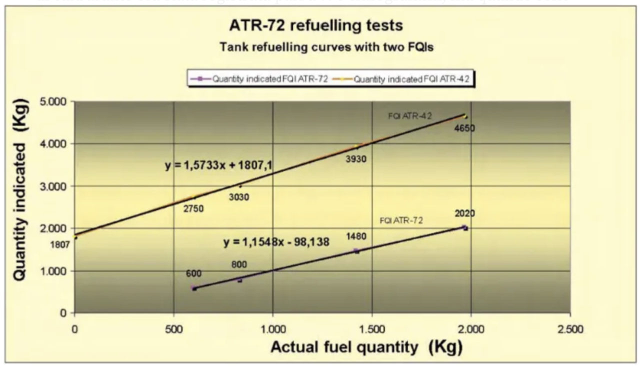


Figure 4.19: Case 2: Tank refueling experimental curves using the two different FQIs

Nobody realized that when the aircraft went into repair, it had 790 kilograms of fuel on board and after that, it had 3100 kilograms of fuel.
This analysis permits finding different violations related to lack of control on the part number applicability and the failure to control the real amount of fuel (**AD000**).
PE204 explains the precondition caused by the possibility of installing a FQI with a different P/N and caused by the FQI catalog not being updated.

The organizational failures depend on improper maintenance procedures and poor training in using the database (**OC005** and **OP003**). The **OR008** is related to the fuel slip that was missed on board.

	First Analysis	Last Analysis
Organizational influence	/	**OC005** ORGANIZATIONAL STRUCTURE IS UNCLEAR OR INADEQUATE **OP003** PROVIDED UNCLEAR, IMPRACTICAL, OR INADEQUATE POLICY, PROCEDURAL GUIDANCE OR PUBLICATIONS **OR008** FAILURE TO PROVIDE ADEQUATE INFORMATION RESOURCES
Supervision/Leadership	**SD002** ALLOWED UNWRITTEN PRACTICES TO BECOME STANDARD	**SD002** ALLOWED UNWRITTEN PRACTICES TO BECOME STANDARD
Preconditions	**PE108** EXTERNAL FORCE OR OBJECT IMPEDED PERFORMANCE **PE202** INSTRUMENTATION AND WARNING SYSTEM ISSUES **PE205** AUTOMATED SYSTEM CREATED A HAZARDOUS CONDITION **PE208** COMMUNICATION EQUIPMENT INEFFECTIVE **PP101** INEFFECTIVE TEAM RESOURCE MANAGEMENT **PC104** CONFUSION **PC203** EMOTIONAL STATE	**PE108** EXTERNAL FORCE OR OBJECT IMPEDED PERFORMANCE **PE202** INSTRUMENTATION AND WARNING SYSTEM ISSUES **PE204** CONTROLS AND/OR SWITCHES **PE205** AUTOMATED SYSTEM CREATED A HAZARDOUS CONDITION **PE208** COMMUNICATION EQUIPMENT INEFFECTIVE **PP101** INEFFECTIVE TEAM RESOURCE MANAGEMENT **PC104** CONFUSION **PC203** EMOTIONAL STATE **PT100** TRAINING CONDITIONS
Unsafe acts	**AE100** PERFORMANCE/SKILL-BASED ERRORS **AE104** UNDER CONTROLLED AIRCRAFT **AE200** JUDGEMENT AND DECISION MAKING ERRORS **AD001** PERFORMED KNOWN DEVIATION	**AE100** PERFORMANCE/ SKILL-BASED ERRORS **AE104** UNDER CONTROLLED AIRCRAFT **AE200** JUDGEMENT AND DECISION MAKING ERRORS **AD000** KNOWN DEVIATIONS **AD001** PERFORMED KNOWN DEVIATION

Figure 4.20: Case 2: Final comparison

This enabled the development of recommendations:

- Check the correctness of the data entered in the FQI catalog on P/Ns and interchangeability. Specializing a person in data entry.
- Provide training in using the database.
- Train pilots to deal with unusual situations.
- Provide training for the entire staff about human factors.

4.3 Case study 3: Lion Air 610

On 29 October 2018, a B737-8 (MAX), flight 610, operated by Lion Air, was carrying out a passenger flight from Jakarta to Pangkal Pinang.[18] Shortly after take-off, the aircraft encountered issues with airspeed, flight control, and altitude. The aircraft disappeared from the radar and lost communication with air traffic control. Less than 13 minutes after take-off, the plane crashed into the water, resulting in the deaths of all 189 occupants. The recorder and the first things found and analyzed showed

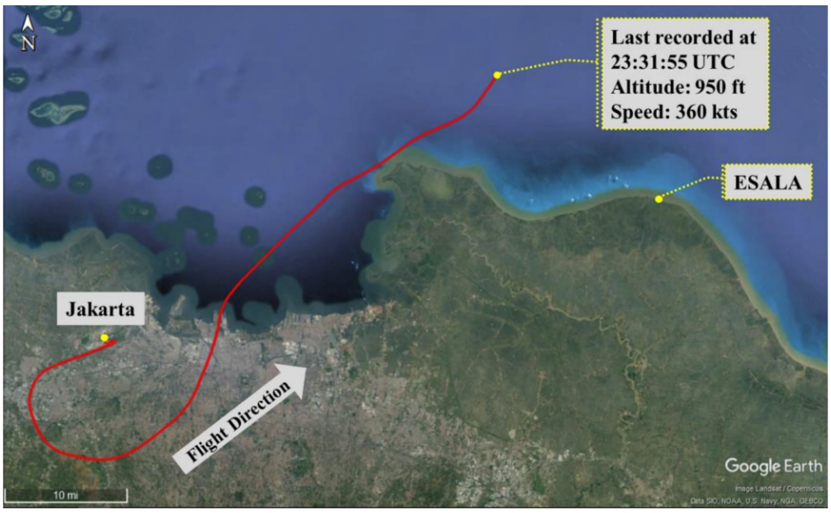


Figure 4.21: Case 3: Map of accident

that a problem with the angle of attack sensor had been reported during the flight. The angle shown in the left display was different from the angle shown in the right one. This led to an incorrect reading of the data provided by the sensors which could be considered the main failure that caused the plane crash. To know whether this main problem is a technician one it is useful to build a diagram that could be used to do a first analysis.

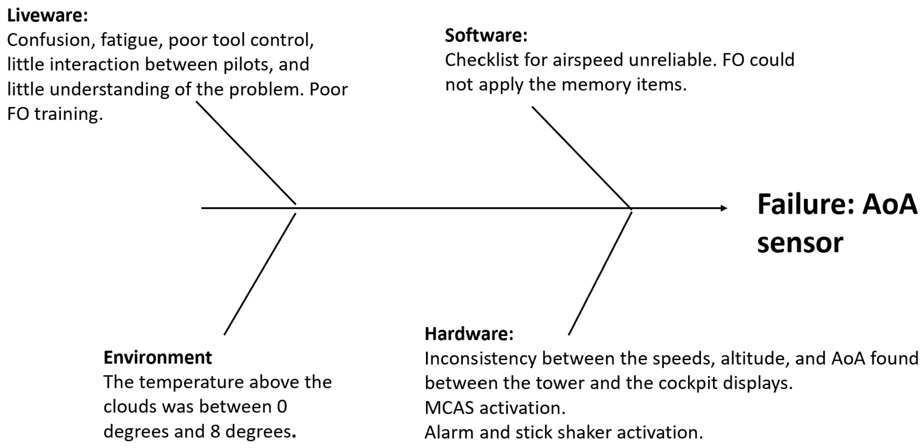


Figure 4.22: Case 3: Fishbone diagram

First, the weather did not affect the performance of the flight and there is a problem related to the procedures necessary in case of airspeed unreliable. The FO could not perform the memory items specified in the procedure. This was due to gaps in training with a lot of unsatisfactory results. There was significant confusion in the cockpit as the pilots did not understand the real reason for the problem. The recordings revealed problems in communication between the captain and the first officer and with the control tower concerning the failure to specify the problem. The crew had poor tool control and seems that they were not familiar with the aircraft. Confusion was also caused by the presence of many alarms in the cockpit.

A violation of procedures is present in this first analysis (**AD003**). This lack of discipline was caused by the pilot who, despite knowing that in an emergency it was necessary to concentrate on securing the aircraft and passengers, decided to continue the flight.

In addition, many concomitant preconditions led to the accident. The **PP111** describes the failure to evaluate the system and the situation after changes had occurred.

PT100 is referred to as the co-pilot lack of knowledge and training. Organizational problems do not come up in this first analysis.

To find them, it is important to analyze the work as it was supposed to be performed by pilots and then define the block diagram of the examined

Organizational influence	/
Supervision/Leadership	/
Preconditions	**PE202** INSTRUMENTATION AND SENSORY FEEDBACK SYSTEMS **PE204** CONTROLS AND/OR SWITCHES **PE205** AUTOMATED SYSTEM CREATED A HAZARD CONDITION **PP111** TASK/MISSION-IN-PROGRESS RE-PLANNING **PT100** TRAINING CONDITIONS **PC101** INATTENTION **PC104** CONFUSION **PC203** LIFE STRESSORS/ EMOTIONAL STATE **PC209** PRESSING
Unsafe acts	**AE200** JUDGEMENT AND DECISION-MAKING ERRORS **AD003** EXTREME LACK OF DISCIPLINE

Figure 4.23: Case 3: HFACS interaction

Liveware	L-Individual- Fatigue / Situational awareness/ Pressure/ Memory capacity/ Decision Judgement/ Experience/ Training/ Knowledge- Competence
Liveware-Liveware	L-L- oral Communication- Misinterpretation L-L- Crew interactions- co-ordination L-L-Worker management- Pressures- Mental pressure
Liveware-Hardware	L-H- Workspace- Alerting and Warnings L-H- Workspace- Information display
Liveware-Software	L-S- Written information- Standard operating procedures L-S- Computers- Computer software
Liveware-Environment	L-E- External- Other factors- Water obstacle

Figure 4.24: Case 3: SHELL interaction

case.
After the alarms sounded, pilots should have been aware that the new B737-8(MAX) was equipped with MCAS. On the B737-8 (MAX), bigger engines are installed more forward on the wing to allow a fuel reduction of 16%. This leads to the aircraft's nose tending upwards and favoring the possibility of stall. To combat this, Boeing has introduced MCAS software that pushes down the nose of the aircraft during certain flight conditions. The incidence sensors send attitude data and if they perceive a change, the MCAS is activated by moving the stabilizers. If the software receives incorrect information, it activates incorrect actions. The crew did not know anything about the MCAS. The first problem therefore lies in the lack of proper training on the features of this new equipment and its functionality. The second one lies in the work of the software that provided incorrect countermeasures. This happened because the AoA sensors malfunctioned.
Maintenance needs to be investigated to see if it is a contributory factor in the accident, while Boeing and Lion Air caused latent errors due to gaps in pilot training and in allowing a pilot with inadequate training, such as the first officer, to fly.

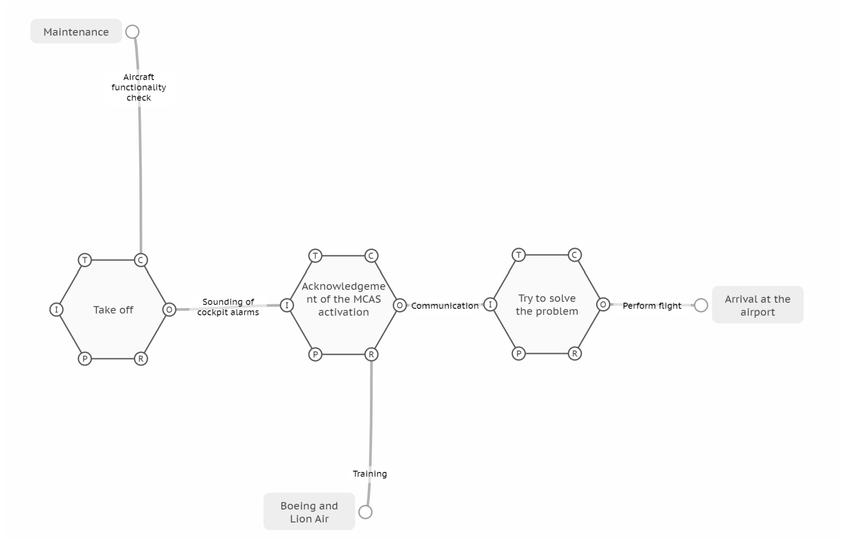


Figure 4.25: Case 3: Work carried out following procedures

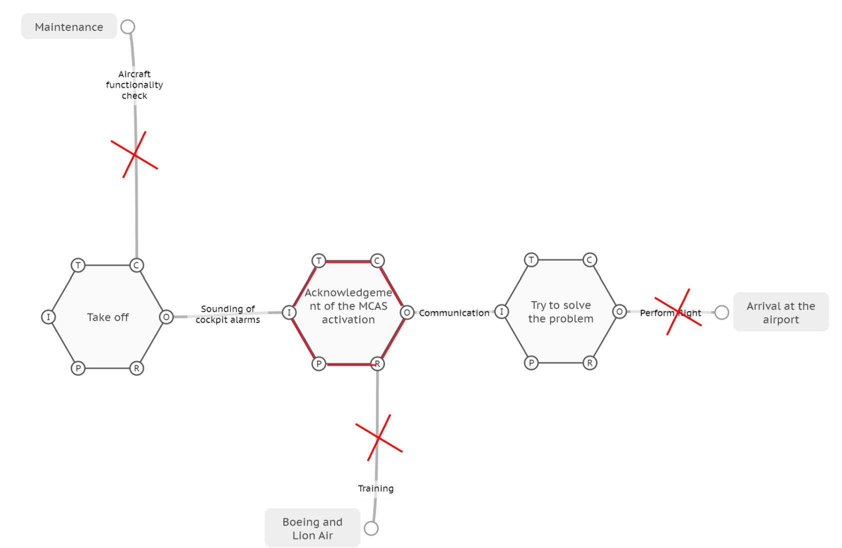


Figure 4.26: Case 3: Work carried out by the pilots

The maintenance department controls directly the aircraft through its operation. It is controlled by two industries BTA and Xtra Aerospace who maintain the AoA sensors and also provide tests to verify installations.

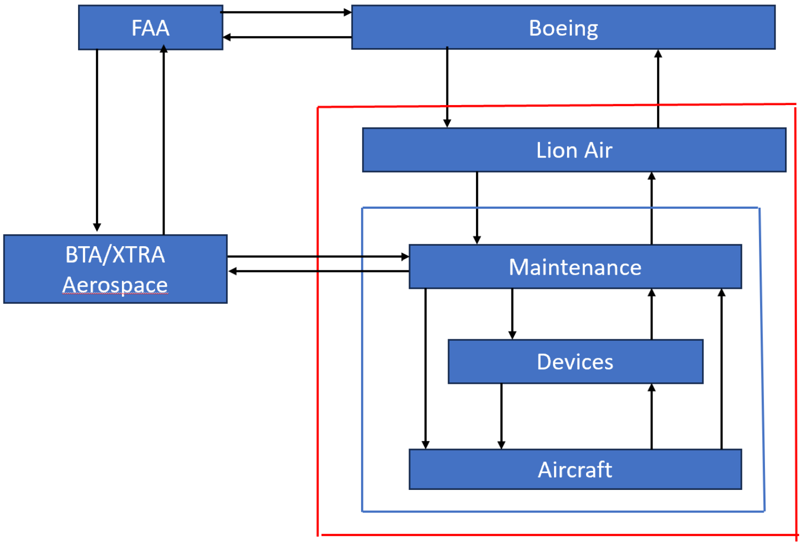


Figure 4.27: Case 3: Control structure

The last analysis gives a lot of latent errors that chained together led to the accident.

- **OR008** referring to Boeing's failure to provide adequate information.
- **OP002** since Boeing had not assessed the risks of adding MCAS to an aircraft already on the market.
- **SI007** Boeing assessed gaps in the AoA disagree implementation. The AoA disagreement was only included if the airline opted for this indicator. Boeing evaluated that it did not affect safety and therefore did not force this implementation.
- **AE107** concerning the speed of the Boeing in the MCAS certification and the failure to simulate certain faults.
- **OP006** and **SI001** concern the FAA, which did not supervise Boeing's work. They also refer to Bat, which provided two possibilities for checking the installation of the AoA sensor, one of which was known to be problematic.
- **PC206** The maintainer did not provide documentation of the installation of the component

	First Analysis	Final Analysis
Organizational influence	/	**OP002** ORGANIZATIONAL PROGRAM OR OPERATION NOT ADEQUATELY ASSESSED **OP006** INADEQUATE PROGRAM MANAGEMENT/GOVERNANCE **OC004** EQUIPMENT CHANGE **OR008** FAILURE TO PROVIDE ADEQUATE INFORMATION RESOURCES
Supervision/Leadership	/	**SI007** FAILED TO IDENTIFY OR CORRECT HAZARDOUS PRACTICES, CONDITIONS, OR GUIDANCE **SI001** INEFFECTIVE SUPERVISORY OR COMMAND OVERSIGHT
Preconditions	**PE202** INSTRUMENTATION AND SENSORY FEEDBACK SYSTEMS **PE204** CONTROLS AND/OR SWITCHES **PE205** AUTOMATED SYSTEM CREATED A HAZARD CONDITION **PP111** TASK/MISSION-IN-PROGRESS RE-PLANNING **PT100** TRAINING CONDITIONS **PC101** INATTENTION **PC104** CONFUSION **PC203** LIFE STRESSORS/ EMOTIONAL STATE **PC209** PRESSING	**PE202** INSTRUMENTATION AND SENSORY FEEDBACK SYSTEMS **PE204** CONTROLS AND/OR SWITCHES **PE205** AUTOMATED SYSTEM CREATED A HAZARD CONDITION **PP111** TASK/MISSION-IN-PROGRESS RE-PLANNING **PT100** TRAINING CONDITIONS **PC101** INATTENTION **PC104** CONFUSION **PC203** LIFE STRESSORS/ EMOTIONAL STATE **PC206** OVERCONFIDENCE **PC209** PRESSING
Unsafe acts	**AE200** JUDGEMENT AND DECISION-MAKING ERRORS **AD003** EXTREME LACK OF DISCIPLINE	**AE107** RUSHED OR DELAYED A NECESSARY ACTION **AE200** JUDGEMENT AND DECISION-MAKING ERRORS **AD003** EXTREME LACK OF DISCIPLINE

Figure 4.28: Case 3: Final comparison

It is recommended to:

- Improve pilot training in case of emergencies.
- Specialise maintainers on the new B737-8(MAX).
- BAT must update its operating manuals.
- Change the design of the cabin to avoid too many alarms hiding the main problem.

In Appendix D.3 it is possible to find the function analysis.

Chapter 5

Conclusion

The analysis can be defined as an assessment of the hazards encountered by those who operate on the aircraft as the work focuses on operations, maintenance, and installation activities.
The hybrid model can be considered as a retrospective analysis since the studies were carried out on incidents that had already occurred. Therefore, the main causes of the event were identified.
However, the recommendations can be defined as input data for future prospective analyses because during the scenario it was possible to find latent causes that could have been a direct part of the accident but fortunately were not. These possible causes must be analyzed to prevent probable accidents.
The study of the final data collected through this deeper analysis, in all three cases, related the latent errors to deficiencies in the supervisory and organizational system about providing adequate guidance and programs to the pilots.

	AF 447	**Tuniter 1153**	**Lion 610**
Organisational influence	OR005	OC005 OP003 OR008	OP002 OP006 OC004 OR008
Supervision/Leadership	SI003 SI007		SI001 SI007

Figure 5.1: Final considerations about latent errors

As can be seen from the table, the analysis showed the presence of **OR000**, errors related to resource support issues, **OP000**, errors related to organizational criteria and procedures, and **OC000**, errors related to organi-

zational culture.
The analysis also found that errors related to supervision related to ineffective control due to lack of training and inaccurate hazard identification.
In all three cases studied, a resource management error is present, **OR005** and **OR008**.
Referring to the cases of a design problem and maintenance one, it is possible to see the constant presence of a latent error given by the organizational culture. In the first case, this is a problem given by the conversions made on an aircraft already on the market, the B737, and then without going through the time-consuming process of design and certification for a new concept aircraft. Meanwhile, the second case refers to the poor organization of the maintenance department.
In conclusion, it could be assumed that in cases relating to organizational and planning problems, such as maintenance and design, an **OC000** and an **OP000** errors will always be present. Whereas an error caused by decisions made by man can lead to violations.
The impact of the AF447 accident was strong. It was the first fatal accident on an Airbus A330 passenger aircraft of the major flag carrier Air France. It brought to light the problem of the "automation paradox". Automation has allowed human error to be the major factor in the accident.
The AF447 disaster has also shown the problem caused by cockpit automation, which allows pilots to disregard key parameters during flight and to concentrate on something else. In this case, this occurred because of the stall alarm. Since the A330 is a fly-by-wire aircraft, inputs are sent to a computer that defines outputs to the ailerons, stabilizer, and rudder. Most of the time the computer works in Normal Law and the pilots were aware that in this regime it is improbable that an aircraft can stall. For the AF447 when the autopilot disconnected there was a switch to Alternative Law so the plane could stall but the pilots paid no attention to this.
This accident led to a change in the way automation is designed at Airbus.

5.1 Next step

As a proposal for possible future development, I propose the application of artificial intelligence.
In a few words, artificial intelligence is a source of knowledge that can be used in two ways.

- In retrospective analysis, which studies an accident that has already taken place, artificial intelligence can be applied to allow rapid and automatic development in the study and classification of errors found in the accident.
- In the prospective analysis, using as input the recommendations provided in previously occurring incidents and providing simulations of possible scenarios triggered by errors found and suggested in the recommendations. [27]

In support of this theory, the article [10] discusses the subject by studying many aviation accidents by AI through machine-learning models. The use of AI could bring to generate rapidly a lot of data. It also led to the following findings:

- Developing new learning organizations by creating new knowledge on previous failures.
- AI works best on linear models and not on systemic models, such as HFCAS.
- It cannot conduct multiple analyses at the same time, for that you would need supercomputers.
- It requires the addition of an interdisciplinary team to supervise its work.

The article proposes the analysis of the AF447 accident by using AI, so it could be possible to conduct a comparison between AI and the Hybrid model findings.

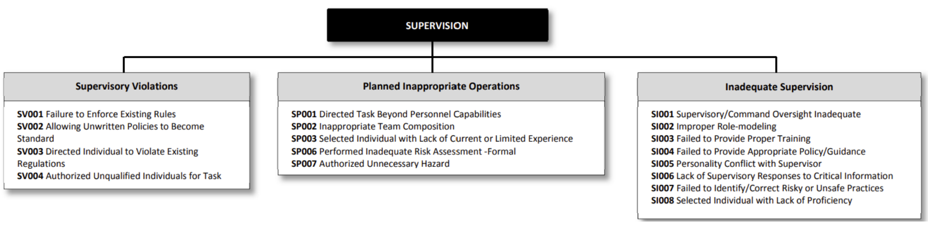


Figure 5.2: Supervision failures in HFACS 7.0 version

First of all, it must be pointed out that AI develops an HFACS analysis with version 7.0 of the taxonomy, which presents supervisory violations with the code **SV000** and not **SD000** as in version 8.0. Furthermore, in the latest version there are also active and latent errors due to training program issues and training conditions, **OT000** and **PT100**.

	Analysis using the Hybrid model	**Analysis using AI**	**Analysis using AI and BEA report**
Organizational Influence	**OR005** FAILURE TO REMOVE INADEQUATE/WORN-OUT EQUIPMENT IN A TIMELY MANNER	**OP006** INADEQUATE PROGRAM MANAGEMENT /GOVERNANCE **OP002** ORGANIZATIONAL PROGRAM OR OPERATION NOT ADEQUATELY ASSESSED **OP005** FLAWED DOCTRINE/PHILOSOPHY	**OP002** ORGANIZATIONAL PROGRAM OR OPERATION NOT ADEQUATELY ASSESSED **OC001** ORGANIZATIONAL CULTURE CREATED INCREASED RISK **OC003** ORGANIZATIONAL OVER-CONFIDENCE OR UNDER-CONFIDENCE IN EQUIPMENT
Supervision/ Leadership	**SI003** FAILED TO PROVIDE EFFECTIVE TRAINING **SI007** FAILED TO IDENTIFY OR CORRECT HAZARDOUS PRACTICES, CONDITIONS, OR GUIDANCE	**SV000** SUPERVISORY VIOLATIONS	**SV001** FAILURE TO ENFORCE EXISTING RULES **SV002** FAILURE TO ENFORCE EXISTING RULES **SP001** DIRECTED TASK BEYOND PERSONNEL CAPABILITIES **SP003** SELECTED INDIVIDUAL WITH LACK OF CURRENT OR LIMITED EXPERIENCE **SP006** PERFORMED INADEQUATE RISK ASSESSMENT -FORMAL **SI001** SUPERVISORY /COMMAND OVERSIGHT INADEQUATE **SI003** FAILED TO PROVIDE EFFECTIVE TRAINING
Preconditions	**PE101** ENVIRONMENTAL CONDITIONS AFFECTED VISION **PE108** EXTERNAL FORCE OR OBJECT IMPEDED PERFORMANCE **PE202** INSTRUMENTATION AND SENSORY FEEDBACK SYSTEMS **PE206** WORKSPACE LIMITATIONS AFFECTED PERFORMANCE **PE208** COMMUNICATION EQUIPMENT INEFFECTIVE **PC103** TASK SATURATION **PC104** CONFUSION **PC203** LIFE STRESSORS/EMOTIONAL STATE **PP101** INEFFECTIVE TEAM RESOURCE MANAGEMENT **PT101** UNTRAINED OPERATOR/ WORKER **PT104** LACK OF PROFICIENCY/EXPERIENCE	**PC103** TASK SATURATION **PC202** PSYCHOLOGICAL PROBLEM **PC204** EMOTIONAL STATE	**PE201** SEAT AND RESTRAINT SYSTEM PROBLEMS **PC307** FATIGUE **PP101** FAILURE OF CREW/TEAM LEADERSHIP
Unsafe acts	**AE108** MISINTERPRETED/ MISREAD INSTRUMENT **AE200** JUDGEMENT AND DECISION MAKING ERRORS	**AE200** JUDGEMENT AND DECISION MAKING ERRORS	**AE103** PROCEDURE NOT FOLLOWED CORRECTLY **AE105** BREAKDOWN IN VISUAL SCAN

Figure 5.3: Final considerations about latent errors

The first difference concerns exactly these codes that are not present in the development of the machine.

Regarding the part of the unsafe act, it can be said that they were all concerned about the failure to recognize the stall and to resolve it but they are presented using different codes.
Discussing organizational influences, AI found deficiencies related to Air France's organizational culture and failures related to the organization of procedures and training.
In addition to the work of the hybrid model, AI allows the addition of other latent errors given by the violation in supervision, especially in allowing unwritten procedures to establish themselves as standard. The preconditions are related to the psychological factor. AI does not recognize problems related to the external and internal environment, but these are detected with the use of the hybrid model. Errors given by the environment are found when analyzing by adding the knowledge given by the BEA report to the machine. Thus **PE201** was found which as a code refers to seat-related problems but no code defines the problem given by frozen pitot probes. This problem, being the trigger for the accident, in the analysis given by the hybrid model, is present in codes **PE108** and **PE202**.
It can be confirmed that AI can be used as a supplementary tool to the work done by the hybrid model by adding useful information to the analysis. However, the analysis of case AF447 showed that the analysis is influenced by interpretation and the work of the machine cannot be considered correct but must be supervised.

Acronym

ADREP Accident/Incident Data Reporting

AoA Angle of Attack

A-SHELL Software-Hardware-Environment-Liveware-Liveware with Airworthiness Requirements

ATC Air Traffic Control

ATCo Air Traffic Controller

ATM Air Traffic Management

ANSV National Agency for the Safety of Flight

BAT Batam Aero Technique

BEA Bureau of Enquiry and Analysis for Civil Aviation Safety

CAST Causal Analysis based on System Theory

CVR Cockpit Voice Recorder

DGAC Direction générale de l'aviation civile

EASA European Union Aviation Safety Agency

ECAM Electronic Centralized Aircraft Monitor

FAA Federal Aviation Administration

FDR Flight Data Recorders

FMS Flight Management Suystem

FO First Officer

FRAM Functional Resonance Analysis Method

HFACS Human Factor Analysis and Classification System

HFACS-ME Human Factors Analysis and Classification- Maintenance Extension

ICAO International Civil Aviation Organisation

KNKT Komite Nasional Keselamatan Transportasi

MCAS Maneuvering Characteristics Augmentation System

NDI Non-Destructive Inspection

NTSB National Transportation Safety Board

PMI FAA Principle Maintenance Inspector

PNF Pilot not flying

ROPS Runway Overrun Protection System

SHELL Software-Hardware-Environment-Liveware-Liveware

STAMP Systems Theoretic Accident Model and Process

STPA System-Theoretic Process Analysis

TAWS Terrein Awareness and Warning System

Appendix A

Deepening statistical analysis

A.1 ICAO Regions

The ICAO Regions used for statistics in this report are based on the Member States accredited to each ICAO regional office. ICAO maintains seven regional offices to provide closer support and coordination for Member States: Asia and Pacific (APAC) Office; Eastern and Southern African (ESAF) Office; European and North Atlantic (EUR/NAT) Office; Middle East (MID) Office; North American, Central American and Caribbean (NACC) Office; South American (SAM) Office; and Western and Central African (WACAF) Office.

Figure A.1: ICAO Regions

A.2 Accident Categories and Dirty Dozen

Code	*Description of **CICTT** Aviation Occurrence Categories (December 2017)*
ARC	Abnormal runway contact: Any landing or takeoff involving abnormal runway or landing surface contact
CFIT	Controlled flight into/towards terrain: In-flight collision or near collision with terrain, water, or obstacle without indication of loss of control.
F-NI	Fire/smoke (non-impact): Fire or smoke in or on the aircraft, in flight, or on the ground, which is not the result of impact.
LOC-I	Loss of control in-flight: Loss of aircraft control while, or deviation from intended flight path, in flight. Loss of control inflight is an extreme manifestation of a deviation from the intended flight path. The phrase "loss of control" may cover only some of the cases during which an unintended deviation occurred.
RAMP	Ground handling: Occurrences during (or as a result of) ground handling operations.
RE	Runway excursion: A veer off or overrun off the runway surface.
RI	Runway incursion: Any occurrence at an aerodrome involving the incorrect presence of an aircraft, vehicle, or person on the protected area of a surface designated for the landing and takeoff of aircraft.

SFC-NP	System/component failure (non-powerplant): Failure or malfunction of an aircraft system or component other than the powerplant.
SFC-PP	System/component failure (powerplant): Failure or malfunction of an aircraft system or component related to the powerplant.
TURB	Turbulence encounter: In-flight turbulence encounter.
UNK	Unknown or undetermined: Insufficient information exists to categorize the occurrence.
USOS	Undershoot/overshoot: A touchdown off the runway/helipad/helideck surface.

Human Factor	Description	Mitigate the risk
Stress	It is the psychological and physiological response that the body enacts toward tasks, difficulties, or events that are evaluated as dangerous.	Take a break. Ask others to monitor your work.
Lack of awareness	Common sense and vigilance tend to fail. Repetition of work reduces attention.	Ask others to check your work. Respect the changes.
Norms	They are unwritten rules that are followed or tolerated by most of the organization.	Ensure that everyone follows the same standard. If it is normal does not make it correct.

Lack of communication	Maintainers must communicate with one another and explain what work has and has not been completed when changing shifts.	Use logbooks and worksheets. Never assume that the work has been completed.
Complacency	People being overconfident in a determined task, can mask the problems.	Expect to find something wrong. Double-check your work.
Lack of knowledge	Maintainers are not keeping up with their knowledge as technology evolves.	Use an updated manual. Ask if you do not know how to do something.
Distraction	Anything that takes your mind off the task that is being done.	Use a checklist. Do not leave tools lying around.
Lack of teamwork	Personality differences in the workplace must be left at the door.	Communicate with the team. Cooperation

Fatigue	Fatigue can cause a decrease in attention and a decreased level of consciousness.	Being aware of symptoms. Being aware of your fatigue limit. Regular sleep.
Lack of resources **Pressure**	Suspend maintenance if resources are not adequate. Pressure is given by the short period for doing the work.	Always have resources available. Do not use non-compatible parts. Verify that pressure is not self-inducted. Communication. Ask for help.
Lack of assertiveness	Do not warn others if something is not working.	Do not compromise your standards. Accept corrective criticisms. Communication.

Appendix B

Analysis method features

HFACS-ME levels and orders

Level 1 factors	Level 2 factors	Level 3 factors
Management conditions	Organisational	Inappropriate processes Inadequate documentation Inadequate design Inadequate resources Communication
	Supervisory	Inadequate supervision Inappropriate operations Uncorrected problem Supervisory misconduct
Maintainer conditions	Medical	Adverse mental state Adverse physical state Physical/mental limitation
	Crew coordination	Inadequate communication Inadequate assertiveness Inadequate adaptibility/flexibility Team work
	Readiness	Training/preparation Certification/qualification Infringement
Working conditions	Environment	Inadequate lighting/light Unsafe weather/exposure Unsafe environmental hazards
	Equipment	Damaged/unserviced Unavailable/inappropriate Dated/uncertified
	Workspace	Confining Obstructed Inaccessible
Maintainer acts	Error	Attention/memory Knowledge/rule-based Skill/technique-based Judgement/decision-making
	Violation	Routine Infraction Exceptional Flagrant

Figure B.1: HFACS-ME division

HFACS Nanocodes

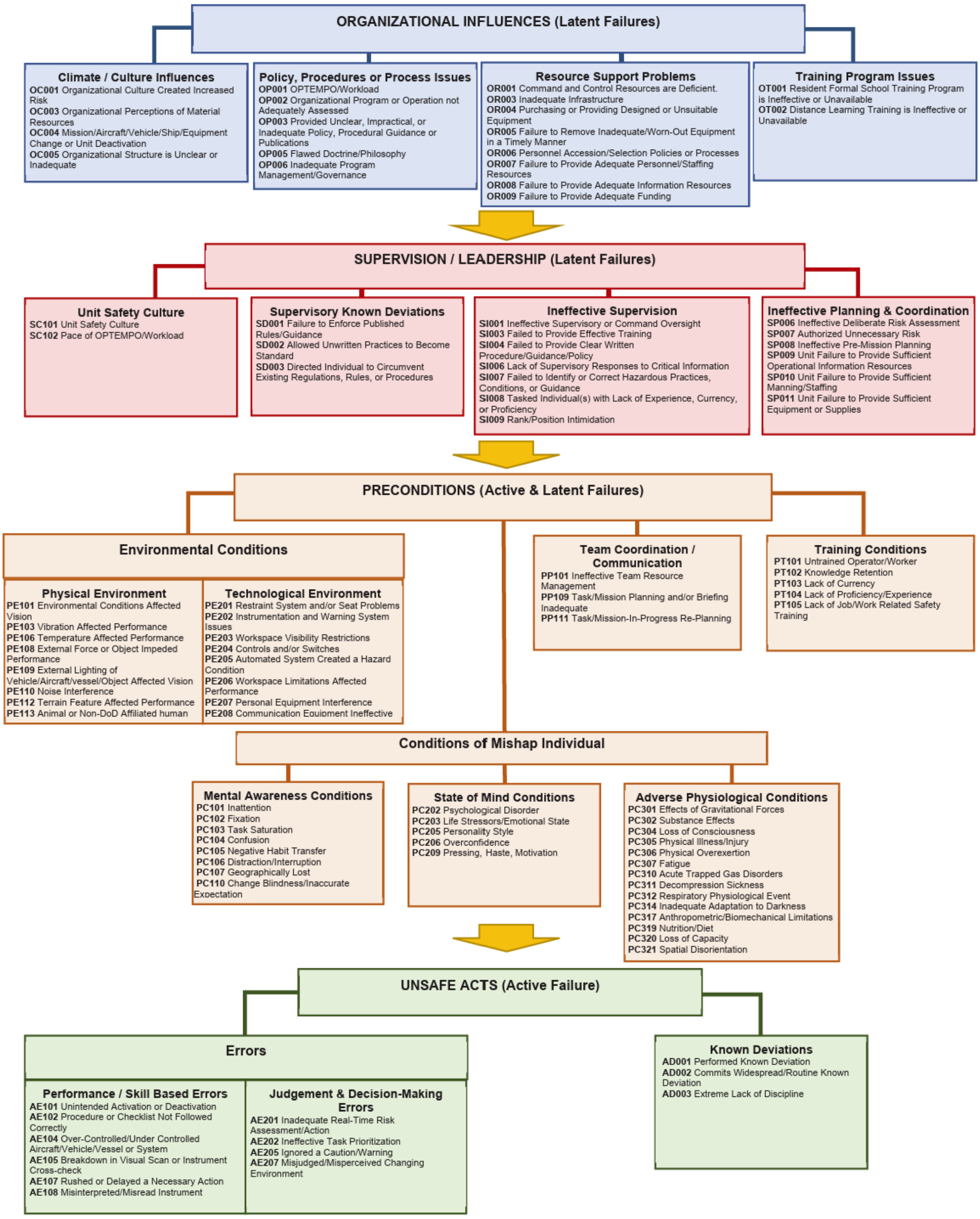


Figure B.2: HFACS 8.0 version

A-SHELL

Lv.1	Level.2		Level.3	
L	L-1	basic qualifications as an aircraft maintenance technician (AMT)	L-1-1	rules and manners
			L-1-2	knowledge about basic maintenance
			L-1-3	basic qualification (assertiveness/complacency/awareness)
	L-2	technical qualification as an AMT	L-2-1	knowledge and practical techniques for planning
			L-2-2	knowledge and practical techniques for opening/cleaning
			L-2-3	knowledge and practical techniques for inspection
			L-2-4	knowledge and practical techniques for repairing
	L-3	airworthiness requirements on AMT	L-3-1	compliance with Hong Kong Airworthiness Requirement (HKAR) 66 Aircraft Maintenance License and approved Maintenance, Repair, and Overhaul (MRO) requirements
L-S	LS-1	airworthiness maintenance procedures	LS-1-1	maintenance manuals
			LS-1-2	implementation of recommended procedures
			LS-1-3	checklist or preflight items
			LS-1-4	repair/overhaul work card
	LS-2	airworthiness regulations on maintenance documents	LS-2-1	minimum equipment list
			LS-2-2	signing maintenance release
			LS-2-3	log book entries
	LS-3	computer-based programmes	LS-3-1	operating the automated systems
L-H	LH-1	operation of equipment	LH-1-1	adequate training on equipment operation
			LH-1-2	use right equipment
			LH-1-3	safety analysis of equipment
	LH-2	improvement in quality and performance of instruments	LH-2-1	maintenance of instruments
			LH-2-2	instrument reliability
L-E	LE-1	Airworthiness regulations on work environment	LE-1-1	well-lighted
			LE-1-2	comfortable working areas (hangars)
			LE-1-3	exposure to noise
			LE-1-4	away from hazards
	LE-2	non-physical factors	LE-2-1	excessive pressure for on-time departure
			LE-2-2	personal matters
	LE-3	company customs and conventions	LE-3-1	normal way in which things are done
	LE-4	enhancement of technical capabilities	LE-4-1	continuing professional development
			LE-4-2	sharing of knowledge and experience
L-L	LL-1	human relationship with other AMTs	LL-1-1	lack of teamwork
			LL-1-2	lack of communications
	LL-2	human relationship with flight crew	LL-2-1	lack of communications
			LL-2-2	misunderstandings
			LL-2-3	disagreements and resolution methods
L-A	LA-1	airworthiness regulations on airline operators	LA-1-1	compliance with Air Operator's Certificates Requirements
	LA-2	airworthiness regulations on working hours and rest	LA-2-1	compliance with Air Navigation Order
	LA-3	airworthiness regulations on aircraft maintenance procedure development	LA-3-1	compliance with Air Operator's Certificates Requirements & airworthiness requirements for Approved Maintenance Organizations
	LA-4	regulatory authority surveillances	LA-4-1	readiness for regulatory authority evaluation and quality inspections
			LA-4-2	response to reporting culture

Figure B.3: A-SHELL checklist

Appendix C

Analysis accident Aloha Airlines

In the FRAM analysis, two things are important: the description of how functions depend on each other and the description of variability. Variability provides an understanding of how functions are interconnected and what unexpected results they can produce.
Essentially in the FRAM, you work with technological, human, and organisational functions.

- Human functions: they can change rapidly and depend on physiological, psychological, and social factors.
- Technological functions: they depend on improper maintenance and fluctuate due to the complicated use of technology.
- Organizational functions: they change according to communication between authorities and are influenced by the legal and physical environment, such as weather conditions.

The Output and the function are evaluated in terms of time and precision. The output provides a coupling between the upstream and downstream functions.
Output is considered **accurate** when the needs of the downstream function are satisfied, **acceptable** when it is used by the downstream function but adjustments are required, and **inaccurate** when it is incomplete or incorrect.
There are five possible couplings between upstream and downstream functions and they are evaluated, as in the picture, according to the potential impact on the downstream function.

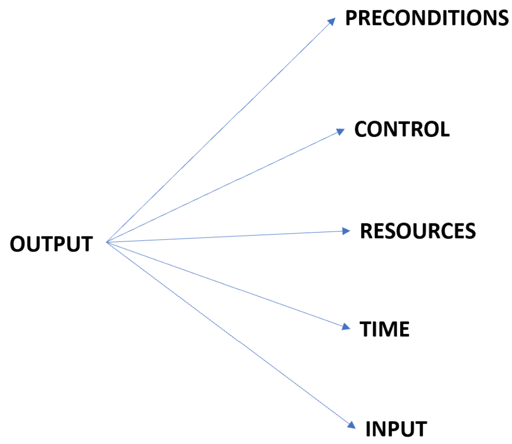


Figure C.1: Function couplings in FRAM analysis

Graphic representation	Meaning
V↑	It means that variability is very likely to increase
V↓	It means that the variability is very likely to be reduced
V↔	It means that the variability remains unchanged

Figure C.2: Potential impact of functions in FRAM analysis

C.1 Funcions in FRAM analysis

Funcion	Output	Downstream Funcion		Time	Effect	Precision	Effect		HFACS
Maintenance	Aircraft functionality check	C	Take off	Omission	Alternative control is sought, if possible	Imprecise	Delays and trade-off with regard to accuracy and precision	V+	SI001 OP006
Acknowledgment on MCAS activation	Communication	I	Try to solve the problem	Omission	Function is not performed	Imprecise	Loss of accuracy precision	V+	OR008 OC004 OP002
Boeing and Lion Air	Training	R	Acknowledgment on MCAS activation	Too late	Possible loss of time	Imprecise	Loss of accuracy precision	V+	OP006
Try to solve the problem	Perform flight	I	Arrival at the airport	Too late	Delays which can lead to increasing use of shortcuts	Imprecise	Insufficient or reduced functionality	V+	SI007 PC206 AE107

Figure C.3: Study of functions

Funcion	**FAA controls the operations of companies**
Description	FAA issues ADs for inspections of fatigue problems.
Input	
Output	Provide adequate inspections and rules
Precondition	
Time	
Control	
Resource	

Funcion	**Boeing executes complete fatigue test on 737**
Description	Boeing performs fatigue test and corrosion tests on connecting parts.
Input	
Output	They could understand problems and solve them
Precondition	
Time	
Control	Provide adequate inspections and rules
Resource	

Funcion	**Crew follow the rules**
Description	The crew follows the ATC and company directives.
Input	Provide adequate inspections and rules
Output	Perform the flight procedures
Precondition	
Time	
Control	
Resource	

Funcion	**Aloha Airlines provides maintenance training**
Description	Aloha Airlines provides training on NDI inspections.
Input	
Output	They could understand problems and solve them
Precondition	
Time	
Control	Provide adequate inspections and rules
Resource	

Funcion	**Performing a flight**
Description	The crew follows the necessary procedures to start and perform a flight.
Input	They could understand problems and solve them
Output	
Precondition	
Time	
Control	Perform the flight procedures
Resource	

C.2 History of flight

5h 00	The first officer checked in with the dispatch office and performed the preflight inspection.
5h 10	The captain arrived and performed his pre-departure duties.
11h 00	There was a change of the first officer.
	The inspections between flights were not required.
13h 25	Departure of Flight 243
A few minutes later	At 24000 feet there was a strange sound and the presence of wind in the cabin (**fuselage part loss**). Start of emergency descent and oxygen activation in the cabin
Meanwhile	The first officer turned the transponder to emergency code 7700 and tried to communicate with Honolulu ATC. The communication failed.
13h 48 min 15	ATC tried to communicate with the flight several times without success.
13h 48 min 35	The first officer changed the radio to the Maui Tower frequency and informed the tower about the decompression and required emergency procedures.
Meanwhile	Tower didn't consider it necessary to call an ambulance.
13h 49	Emergency coordination began between the Honolulu Center and Maui Approach Control.
13h 50 min 58	The local controller requested the flight to switch to approach frequency. The request was acknowledged but the flight didn't change the frequency.
13 h 53 min 44	The first officer required assistance for passengers.
Meanwhile	The captain began to slow the aircraft during descent.
13 h 55 min 05	The first officer advised the tower that they had a problem with the nose gear. (Problem about the indicator light). The engine 1 didn't work.
13 h 58 min 45	The aircraft landed and emergency evacuation.
Before the accident	A passenger observed a longitudinal fuselage crack.

Figure C.4: History of flight

C.3 Swiss Cheese visualisation

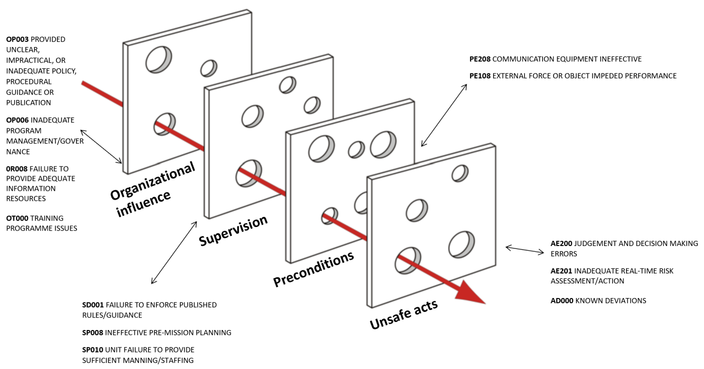


Figure C.5: Graph of Swiss Cheese model

Appendix D

Analysis case study

D.1 Case 1: AF 447

D.1.1 Funcions in FRAM analysis

Funcion	Output	Downstream Funcion		Time	Effect	Precision	Effect		HFACS
Pilot takes control	Provides power and does not change the direction of the aircraft	I	Successfully overcoming the critical phase	Omission	Function is not performed	Imprecise	Loss of accuracy precision	V+	SI007
Air France	Provides procedures in case of autopilot off and stall risk	C	Pilot takes control	Too early	Instructions/guidance may be missed	Imprecise	Delays and trade-off with regard to accuracy and precision	V+	SI003

Figure D.1: Study of functions

Funcion	Pilot takes control
Description	The pilot tries to solve amy problems during the flight
Input	
Output	Provides power and does not change the direction of the aircraft
Precondition	
Time	
Control	
Resource	

Funcion	Air France
Description	The company provides training for the crew members. In this specific case training adapts to stall problem
Input	
Output	Provides procedures in case of autopilot off and stall risk
Precondition	
Time	
Control	
Resource	

D.1.2 Swiss Cheese visualisation

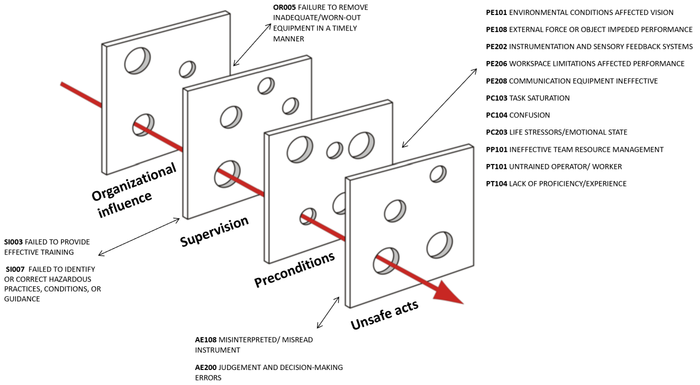


Figure D.2: Graph of Swiss Cheese model

D.2 Case 2: Tuniter 1153

D.2.1 History of flight

August 5th, 2005	
Planning	TS-LBB aircraft was used for 5 flight routes. The captain, involved in the accident, flew 4 times, and the co-pilot, that was involved in the accident, twice.
1st captain flight	Reported a problem with the FQI. The value indicating the right tank was incorrect.
End of 4th flight	The captain reported the problem of FQI on the aircraft's logbook.
During the evening	The technician didn't find on the database the FQI P/N 748681-2, S/N 179, or those associated with ATR72. FQIs with that P/N were not entered.
During the evening	The technician saw on the software that P/N 748-465-5AB was applicable at ATR42 and ATR72. (Incorrect information)
During the evening	Noted that there was interchangeability with FQI P/N 749-158. Found it on the database and decided to use it for the installation.
During the night	The technician, replacing the piece, followed the ATR instructions, that not require any checking on the correctness of information provided by the device.
During the night	The technician did not check the applicability of the device.
	Instead of the actual value of 790 kg, the new FQI indicated 3050 kg as the remaining fuel quantity.

Figure D.3: Flight history on August 5

August 6th ,2005	7 flights planned for the TS-LBB aircraft.
1st flight planned	1400 kg of fuel was requested to do the route but the tanks were full of 3100 kg, so it was necessary defueling. The aircraft didn't fly.
2nd flight planned	A captain refused to use the plane because he had previously experienced problems with nose wheel steering. The aircraft didn't fly.
10h 00	FD contacted the flight captain by phone to ask if the quantity of fuel indicated (3100 kg) would be enough to complete the route. The captain replied that he would decide after viewing the documents.
11h 00	The co-pilot prepared the operation documents. Pre-calculated the quantity of fuel needed 4200 kg.
Then	The captain decided to refill only 3800 kg of fuel. So 700 kg of fuel was necessary to add.
11h 30	Ended of refilling. None of the operators realized that only 465 kg of fuel had been added.
	The captain noticed that the fuel slip for the refueling from the quantity of 790 kg to 3100 kg was missing. The FD will provide it upon return of the flight.
	The captain decided to fly without the fuel slip.
12h 05	Take off from Tunis.
13h 46	Arrived in Bari.
	In Bari, the quantity of fuel was 2300kg, different from the quantity planned (about 2700 kg).
13h 55	Necessary refill. Instead of the required 400 kg only 265 kg were added.
12 h 19	Requested permission to start the engines.
12 h 22	The permit was granted.
12 h 25	Authorization for the flight was received.
12 h 30	Authorization for take off.
12 h 32	Take off.
12 h 34 min 55	Communication to Brindisi ACC to flight at FL 190. This was granted.
12 h 49 min 40	Requested ACC to go up to FL 210 and they responded by changing the radio frequency and contacting Roma ACC.
12 h 50 min 20	The flight contacted Roma to go up at FL 210. This was granted.
13 h 01 min 46	Requested to go at FL 230. This was granted.
13 h 17 min 03	Requested authorization to proceed to waypoint TUPAL.
13h 21 min 36	Requested to pass at FL 170 due to unspecified technical problems (right engine).
Meanwhile	Acoustic warnings in the cockpit(FEED LO PR warning).
	The PNF started reading the checklist procedures for the failures.

Figure D.4: Flight history on August 6, part 1

	Rome ACC did not authorize this and announced that they would go down to FL 190.
	The captain requested the co-pilot to stop reading because also the left engine shut down.
13 h 23	The flight communicated that wanted to land in Palermo because also the left engine shut down.
	Roma ACC gave the authorization and asked if specific assistance was needed but there was an overlap in communication and this was not heard by the crew.
	The flight transmitted the MAYDAY declaration.
13 h 24 min 19	The flight transmitted another MAYDAY declaration and requested to be vectored to Palermo.
Meanwhile	The captain decided to call the airline engineer to the cockpit. Some attempts to restart the engines were made.
	Rome ACC did not provide the information but instructed to contact Palermo on frequency 120.2 MHz.
Meanwhile	Rome ACC contacted by phone Palermo and informed that ATR72 had declared an emergency due to a technical fault but did not specify it.
13 h 25	The flight contacted Palermo, confirmed the emergency, and asked three times the distance to the airport.
	The controller did not understand the request and thanks to another aircraft on the same frequency, there was a bridge transmission.
	The crew realized that it was impossible to land at Palermo and requested a landing site near it.
	The captain called the flight attendant and asked him to prepare the passengers for a ditching.
	The procedures to prepare the passengers went well but some in confusion inflated their life jackets before impact.
13 h 31 min 52	Palermo APP requested information on the number of passengers, fuel load, and dangerous goods.
13 h 33 min 53	Palermo APP informed the distance from the airport.
13 h 35	The flight declared the inability to land in Palermo and the likelihood of ditching.
	The captain asked the co-pilot to read the ditching checklist. But he needed help from him so the checklist was not completed.
13 h 37 min 08	Loss of communication.
13 h 38 min 05	Ditching.

Figure D.5: Flight history on August 6, part 2

D.2.2 Funcions in FRAM analysis

Funcion	Output	Downstream Funcion		Time	Effect	Precision	Effect		HFACS
Change of angle of thrusters	Reducing speed and friction	I	Arrival in Palermo	Omission	Function is not performed	Imprecise	Loss of accuracy precision	V+	PT100 PE204
Second engine shutdown	Reducing speed and friction	I	Arrival in Palermo	Omission	Function is not performed	Imprecise	Loss of accuracy precision	V+	OP003 PT100

Figure D.6: Study of functions

Funcion	Change of angle of thrusters
Description	When an engine is not working, it is necessary to reduce speed and flag the thrusters
Input	Beginning of the glide
Output	Reducing speed and friction
Precondition	
Time	
Control	
Resource	

Funcion	Second engine shutdown
Description	The second engine stops working
Input	
Output	Reducing speed and friction
Precondition	
Time	
Control	
Resource	

D.2.3 Swiss Cheese visualisation

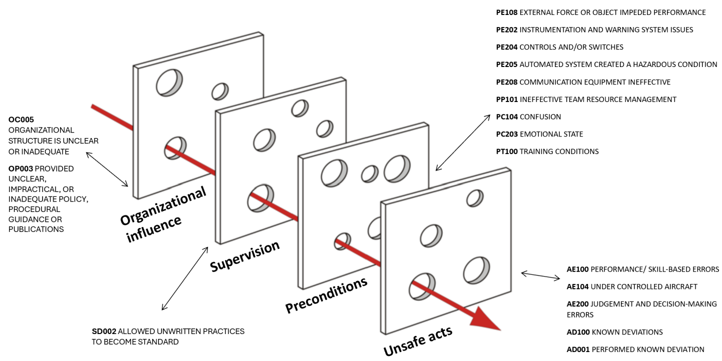


Figure D.7: Graph of Swiss Cheese model

D.3 Case 3: Lion Air 610

D.3.1 History of flight

Preflight briefing	DMI of Automatic Directional Finder (ADF).
23h 15	The crew performed before the taxi checklist and the DFRD recorded pitch trim was 6.6 units.
23h 18	The crew contacted Jakarta Tower and followed the instructions for the take-off.
23h 20	The first officer required 80 knots and the DFDR recorded the airspeed indicator on the Captain's Primary Flight Display (PFD) indicated 79 knots while the First Officer's (FO) PFD indicated 81 knots. The DFDR also recorded the difference angle between the left and right Angle of Attack (AOA) sensor, which was about 21°. The DFDR indicated that the Flight/Director (F/D) on the Captain's Primary Flight Display (PFD) showed 1°down, while the first officer's PFD showed 13° up.
23h 20min 32	EGPWS played V1. The captain's V1 was 140 knots and the FO was 143 knots.
23h 20min 33	Activation of stick shaker.
23h 20min 37	The take-off configuration warning sound.
23h 20min 40	Take off
23h 20 min 44	The FO called "Auto Brake Disarm" and advised the Captain of "Indicated Airspeed Disagree". The left indicated airspeed was 164 knots and the right was 173 knots. The FO whether the Captain intended to return to the airport. The Captain did not respond to the FO question and did not provide acknowledgment. The FO repeated the call "auto brake disarmed" which was acknowledged by the Captain.
23h 21	Landing gear moved UP and requested to contact TE (Terminal East).
23h 21min 12	Altitude disagree. (PF was 340 feet and FO was 570 feet)
23h 21min 28	TE required to go at FL 270. The FO asked the tower the information about the altitude (900 feet). On the PF display was 790 feet and on the FO display was 1040 feet.
23h 21min 44	The captain instructed the FO to perform memory items for airspeed unreliable but he did not respond. FO proposed to fly downwind but PF did not accept and asked to request clearance to any holding point.
23h 21min 45	The aircraft turned to the left. The captain's altimeter read 1310 feet and the FO 1540 feet.
23h 21min 52	TE asked for a description of the problem. The crew reported a flight control problem
23h 22	Passage from Flap 5 to Flap 1. TE saw on radar that the aircraft was going down.
23h 22min 30	Communication with TE about altitude.
23h 22min 32	Bank angle alarm.

Figure D.8: Flight history on October 29, part 1

	Rome ACC did not authorize this and announced that they would go down to FL 190.
	The captain requested the co-pilot to stop reading because also the left engine shut down.
13 h 23	The flight communicated that wanted to land in Palermo because also the left engine shut down.
	Roma ACC gave the authorization and asked if specific assistance was needed but there was an overlap in communication and this was not heard by the crew.
	The flight transmitted the MAYDAY declaration.
13 h 24 min 19	The flight transmitted another MAYDAY declaration and requested to be vectored to Palermo.
Meanwhile	The captain decided to call the airline engineer to the cockpit. Some attempts to restart the engines were made.
	Rome ACC did not provide the information but instructed to contact Palermo on frequency 120.2 MHz.
Meanwhile	Rome ACC contacted by phone Palermo and informed that ATR72 had declared an emergency due to a technical fault but did not specify it.
13 h 25	The flight contacted Palermo, confirmed the emergency, and asked three times the distance to the airport.
	The controller did not understand the request and thanks to another aircraft on the same frequency, there was a bridge transmission.
	The crew realized that it was impossible to land at Palermo and requested a landing site near it.
	The captain called the flight attendant and asked him to prepare the passengers for a ditching.
	The procedures to prepare the passengers went well but some in confusion inflated their life jackets before impact.
13 h 31 min 52	Palermo APP requested information on the number of passengers, fuel load, and dangerous goods.
13 h 33 min 53	Palermo APP informed the distance from the airport.
13 h 35	The flight declared the inability to land in Palermo and the likelihood of ditching.
	The captain asked the co-pilot to read the ditching checklist. But he needed help from him so the checklist was not completed.
13 h 37 min 08	Loss of communication.
13 h 38 min 05	Ditching.

Figure D.9: Flight history on October 29, part 2

D.3.2 Funcions in FRAM analysis

Funcion	Output	Downstream Funcion		Time	Effect	Precision	Effect		HFACS
Maintenance	Aircraft functionality check	C	Take off	Omission	Alternative control is sought, if possible	Imprecise	Delays and trade-off with regard to accuracy and precision	V+	SI001 OP006
Acknowledgment on MCAS activation	Communication	I	Try to solve the problem	Omission	Function is not performed	Imprecise	Loss of accuracy precision	V+	OR008 OC004 OP002
Boeing and Lion Air	Training	R	Acknowledgment on MCAS activation	Too late	Possible loss of time	Imprecise	Loss of accuracy precision	V+	OP006
Try to solve the problem	Perform flight	I	Arrival at the airport	Too late	Delays which can lead to increasing use of shortcuts	Imprecise	Insufficient or reduced functionality	V+	SI007 PC206 AE107

Figure D.10: Study of functions

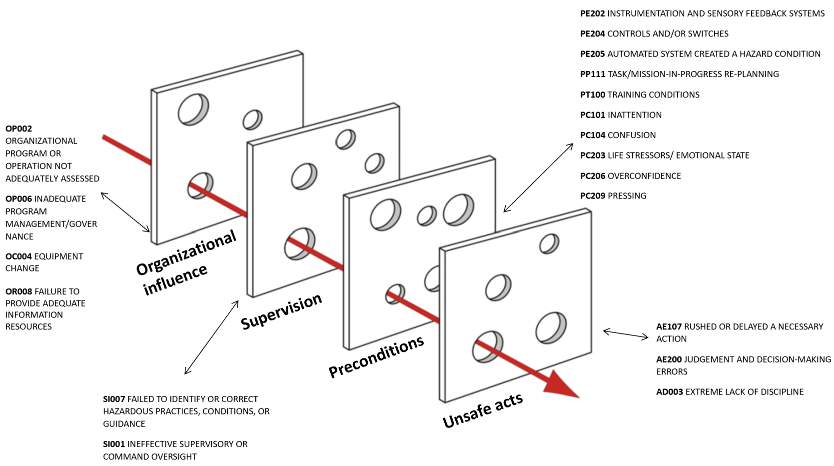
Funcion	**Try to solve the problem**
Description	They are the actions of pilots to try to solve problems
Input	Communication
Output	Perform flight
Precondition	
Time	
Control	
Resource	

Funcion	**Boeing and Lion Air**
Description	It includes all organisational and training programmes
Input	
Output	Training
Precondition	
Time	
Control	
Resource	

Funcion	**Acknowledgment on MCAS activation**
Description	The MCAS is a software created by Boeing
Input	Sounding of cockpit alarms
Output	Communication
Precondition	
Time	
Control	
Resource	Training

Funcion	**Maintenance**
Description	All the work necessary to allow the aircraft to function properly
Input	
Output	Aircraft functionality check
Precondition	
Time	
Control	
Resource	

D.3.3 Swiss Cheese visualisation



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