Politecnico di Torino

Master's Degree in Aerospace Engineering

Master's Degree Thesis

Study of Commercial Aviation Incidents applying the Functional Resonance Analysis Method (FRAM) to identify Commonalities in Human Factors for Aviation Safety

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Abstract (English version)

In a context characterized by rapid changes and strong economic and technological influences, safety remains the top priority in the aviation sector. Risk assessment and incident analysis are fundamental tools needed to improve Flight Safety, representing a central focus of multiple academic and industrial studies.

The purpose of this thesis is to explore and expand the *Functional Resonance Analysis Method (FRAM)*, an innovative methodology born to this end. By embracing the Safety-II philosophy, FRAM enables the analysis of complex non-linear socio-technical systems as well as the interactions within it, offering an integrated approach by complementing more traditional methods, which are, instead, based on a linear and proportional framework.

The work focused on studying the performance variability of the different functions that describe the FRAM model of an aircraft during the approach phase. The goal was to look for commonalities between them, ultimately aiming at evaluating which human factors might play a crucial role, in order to adopt specific safety measures to further improve aviation safety.

To this end, the analysis considered a near-miss event that occurred on February 9, 2003, involving a Boeing 737-36N during its approach to Oslo Gardermoen Airport under adverse weather conditions, with malfunctions of ground infrastructures, poor avionics and degraded ATC communications. The results were then compared to other occurrences examined, classified under the Controlled Flight Into Terrain (CFIT) category, to draw relevant conclusions.

Abstract (Italian version)

In un contesto caratterizzato da rapidi cambiamenti e forti influenze economiche e tecnologiche, la sicurezza rimane la priorità assoluta nel settore aeronautico. La valutazione del rischio e l'analisi degli incidenti aerei sono strumenti fondamentali per migliorare la Flight Safety, rappresentando oggetto di interesse di molti studi accademici e industriali.

Lo scopo di questa tesi è, dunque, quello di approfondire ed espandere il *Functional Resonance Analysis Method (FRAM)*, una metodologia innovativa nata proprio con questo fine. Basato sulla filosofia della Safety-II, il FRAM consente di esaminare sistemi socio-tecnologici complessi e non lineari, nonchè le interazioni al loro interno, permettendo di ottenere un approccio integrato grazie alla sua complementarietà con metodi più tradizionali, caratterizzati, invece, da una visione lineare e proporzionale.

Il lavoro si è incentrato sullo studio della variabilità della performance relativa alle diverse funzioni che compongono il modello FRAM di un aeromobile in fase di avvicinamento. L'obbiettivo è stato quindi la ricerca di caratteristiche comuni al fine di valutare quali fattori umani ricoprano un ruolo cruciale in questa fase, permettendo di adottare, o potenziare, alcune misure di sicurezza, per rendere sempre più sicuro il settore aeronautico.

A tale scopo è stato preso in esame un mancato incidente (near miss) accaduto il 9 febbraio 2003 ad un Boeing 737-36N durante l'avvicinamento all'aeroporto di Oslo Gardermoen con condizioni meteo avverse, malfunzionamenti alle infrastrutture di terra, degradamento delle comunicazioni ATC e un sistema avionico vulnerabile. I risultati ottenuti sono quindi stati confrontati con altri incidenti esaminati, appartenenti alla categoria del Controlled Flight Into Terrain (CFIT), per trarre le dovute conclusioni.

Acknowledgements

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A special thank you goes to Ten. Col. Antonio Schifano for accepting to be my thesis co-supervisor. His operative experience and knowledge have been extremely helpful for developing and improving the analysis. I am grateful for the time he dedicated to me, being always available to assist and answer my questions.

Thank you to all my friends, recent and old. I cannot thank you enough for the support you have provided me in facing and overcoming the challenges I encountered during this journey.

Last but not least, my biggest thank you can only go to my parents for always being by my side. Their love and support have been a constant source of strength and motivation throughout these years and I could not be here without them.

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List of Acronyms

A/C	Aircraft
AD	Aerodrome
AFIS	Aerodrome Flight Information Service
AGL	Above Ground Level
ANSV	Agenzia Nazionale per la Sicurezza del Volo
AP	Autopilot
APP, APPR	Approach
ATC	Air Traffic Control
ATM/ANS	Air Traffic Management and Air Navigation Services
ATS	Air Traffic Services
B	Background (function type)
C	Crew
CFIT	Controlled Flight Into Terrain
DME	Distance Measuring Equipment
EADI	Electronic Attitude Director Indicator
EFIS	Electronic Flight Instrument System
F	Foreground (function type)
FIS	Flight Information Service
FRAM	Functional Resonance Analysis Method
GPWS	Ground Proximity Warning System
GS	Glide Slope
HF	Human Factors
ICAO	International Civil Aviation Organization
ILS	Instrumental Landing System

LOC	Localizer
MSL	Mean Sea Level
NDB	Non-Directional Beacon
NOTAM	Notice To Airmen
PF	Pilot Flying
PNF	Pilot Not Flying
RWY	Runway
S	On-board Systems
TWR	Tower
VOR	Very-high-frequency Omni-directional Range

1 Introduction

Safety has always represented a main requirement in the aviation field, being of paramount importance for both design and operations companies.

According to ICAO's Annex 19 [19], safety is defined as *"The state in which the risks associated with aviation activities, related to, or in direct support of the operation of aircraft, are reduced and controlled to an acceptable level"*, a principle that has driven the industry to continuously improve its standards. Indeed, new technologies and best practices, backed by rigorous regulations, have always been key features of the evolution of flight safety among operators, manufacturers and regulating agencies.

Moreover, ICAO's Annex 13 [18] mentions another important tool to achieve this goal: the analysis of aviation occurrences. Investigating such events allows us to identify potential hazards and to prevent them from happening again in the future, by adopting specific, subsequent, countermeasures.

This work falls within this framework.

The main purpose is to study aviation occurrences with similar features in order to investigate whether there might be commonalities among them and to analyze what factors may play a role in their onset, ultimately aiming at finding mitigations to counter them and improve flight safety.

To this end, the Functional Resonance Analysis Method (FRAM) has been employed. FRAM is a modern and innovative incident analysis and risk assessment methodology, born to address the study of complex non-linear socio-technical systems, nowadays the standard structure of the aviation industry. Being based on the Safety-II philosophy, its choice also allows us to demonstrate its capability in integrating traditional methods while still being open to improvements and further development.

In this work three occurrences have been analysed: the first is a near-miss event that took place on February 9, 2003, involving a Boeing 737-36N during its approach to Oslo Gardermoen Airport under adverse weather conditions, with malfunctions of ground infrastructures, poor avionics and degraded ATC communications. Subsequently, a database of similar occurrences has been created and two more have been selected for comparison. These last two occurred during the approach phase in Cagliari and in Narsarsuaq (GRL) and are both classified under the Controlled Flight Into Terrain (CFIT) category.

1.1 A brief overview on modern safety occurrences

Significant advancements in technology have always been present in the history of modern aviation and this has contributed to a steady reduction in the incidents over the years.

Such decreasing trend has already been established for decades, as it can be seen in Figure 1.1 taken from *Boeing's Statistical Summary of Commercial Jet Airplane Accidents*, regardless of the stable raise in the total number of passenger flights [23].

Nonetheless, continuous activity is required to adapt to a changing world, addressing the new emerging risks: if initially safety efforts were mainly focused on technical and mechanical failures, attention has now shifted towards human factors, which are estimated to contribute to 70–80% of modern aviation incidents.

Human factors play indeed a crucial role in these occurrences: not only these factors affect crew members, but they have an impact on every component of the complex socio-technical system defined by the industry, from management officers to aerodrome operators and ATC staff, representing therefore one of the most critical aspects in the contemporary aviation world.

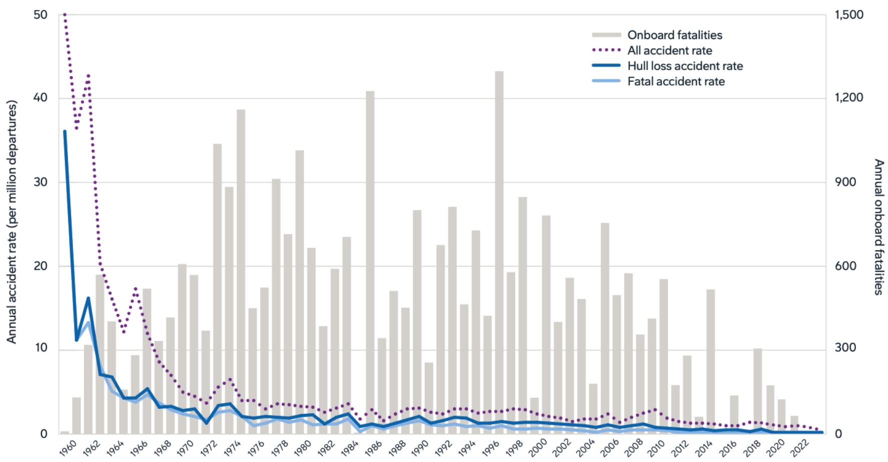


Figure 1.1: Fatalities involving large aeroplane passenger and cargo operators worldwide (source: [23])

Human factors are multiple and can affect each element of the system differently, but decision-making and task performance-related factors, as well as situational awareness and physiological events, are among the ones with the most frequency.

This can be seen in Figures 1.2, 1.3 and 1.4 which depict the application of high-level human factors event codes to occurrences involving crew, Air Traffic Management and Air Navigation Services (ATM/ANS) and to Aerodrome and ground handling personnel, dating from 2019 to 2023, taken from the EASA 2024 Annual Safety Report. [12]

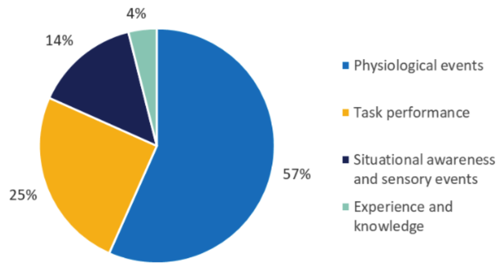


Figure 1.2: Crew of commercial aircraft

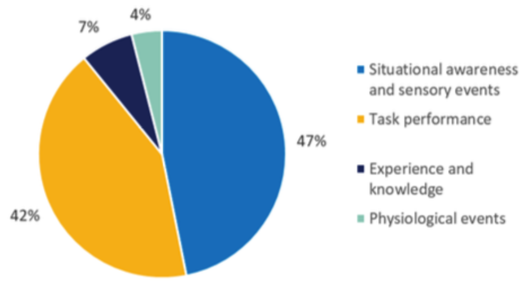


Figure 1.3: ATM/ANS personnel

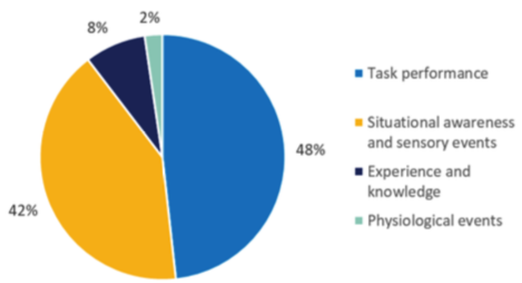


Figure 1.4: Aerodrome and ground handling personnel

Another common trend is relative to the phase during which these events occur. Statistics shows how the *Approach* and *Landing* phases are the ones most prone to accidents, as it can be seen in Figure 1.5, depicting the distribution of occurrences relative to worldwide commercial airplanes from 2014 to 2023 [23].

This can generally be related to the high-workload situation that these phases represent, where a significant number of tasks is performed by both humans and machine systems, though many factors can come into play.

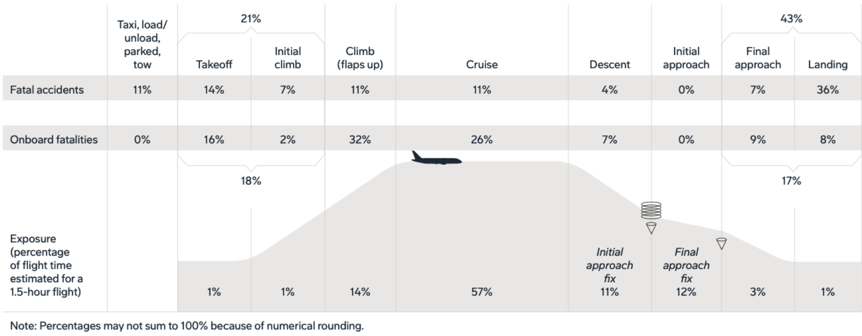


Figure 1.5: Distribution of 2014-2023 occurrences between different flight phases (source: [23])

Finally, aircraft loss of control, runway excursion, fuel-related events and terrain collision (especially CFIT) are the most frequent accident outcomes. This is again a common trend over the years, as statistics relative to the past decade show (Figure 1.6).

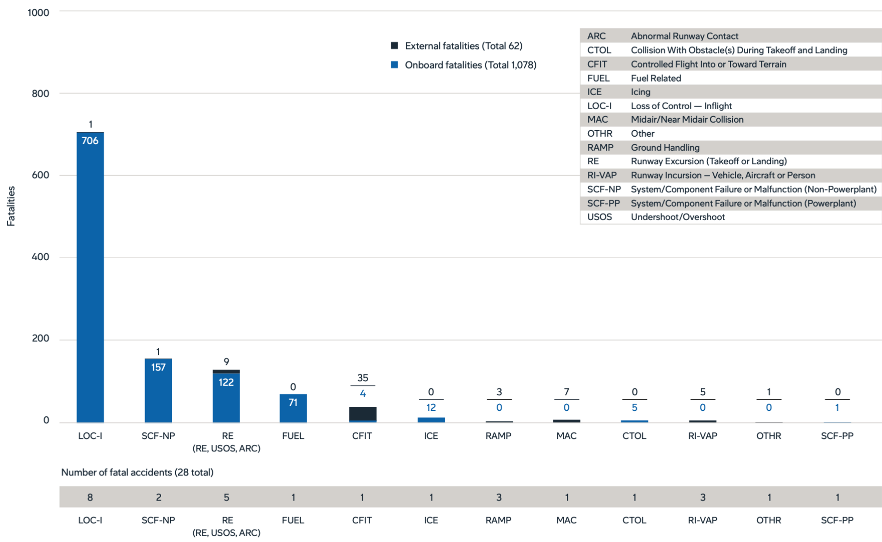


Figure 1.6: Distribution of 2014-2023 occurrences between different flight phases (source: [23])

1.2 FRAM introduction

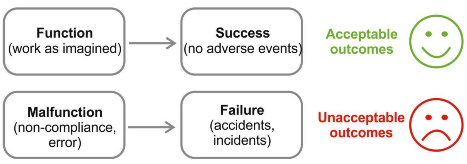
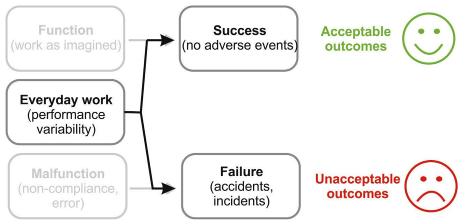
The *Functional Resonance Analysis Method (FRAM)* is a systematic approach introduced by Erik Hollnagel in 2012, used to create a model, called a FRAM model, of a complex socio-technical system, in order to analyze the interdependencies within its different components and to study the variability of a single constituent function as well as how it can propagate to the others, ultimately affecting the whole system.

As mentioned, such systems are nowadays the standard structure of the aviation industry, making FRAM a powerful tool for accidents analysis and risk assessment activities.

The following sections present an initial description of the general safety framework in which this work is collocated, followed by a few recalls on basic FRAM concepts.

1.2.1 Safety-I vs Safety-II

The table below presents the main differences between Safety-I and Safety-II frameworks:

Safety I	Safety II
The Safety-I philosophy is based on the bimodal view that things go right or wrong because of different causes: whether a work, or activity, will yield an acceptable or an adverse outcome is solely due to two different modes of functioning. This assumption is the backbone of models such as the *Domino model* or the *Swiss Cheese model*, characterized by a proportional cause-effect logic where any outcome is the direct consequence of a preceding cause, that has generated it to a proportionate extent. According to this concept it would be ideally possible to find out all the underlying causes which would, in turn, prevent every possible accident from happening. This is the so-called *'Zero-Accident'* vision which, unfortunately, is only suitable for relatively simple systems. [13][14][16]	Safety-II is an innovative concept based on the principles of *Resilience Engineering*, whose main concern is *'ensuring that everything goes right'* rather than focusing on *'avoiding that something goes wrong'*. A completely different view, which stems from the fundamental assumption that the causes leading to positive and negative outcomes are the same. Indeed, it has been observed that people adapt to the always-changing work situations they face every day, constantly adjusting their performance to ultimately reach the desired outcome, even though sometimes this may lead to negative results. This variability is the true reason why the majority of times things go right, rather than because they go as planned. This notion is the main focus of a Safety-II analysis. [13][14][16]
	

The work done in this project embraces the Safety-II framework. Specifically, the Safety-II principles have been interpreted in *operational terms*, in order to achieve the objectives of the project.

This decision stems from a fundamental need of the aviation industry: to produce valuable and feasible countermeasures to address the findings of an investigation.

For this purpose, concrete procedures are necessary. Abstract or excessively theoretical solutions, which may seem sophisticated on paper but offer no practical value in a real-world scenario, are instead of no use. An investigation must, indeed, be able to suggest plausible actions to fix what went wrong, by putting forward new barriers or strengthening the ones already implemented, regardless of the methodology adopted.

Moreover, the Safety-II approach followed does not want to be a mere critique towards the 'old' Safety-I methods, but rather it is intended to expand the current analysis capacity, found to be suboptimal in addressing complex socio-technical systems.

Being based on the Safety-II philosophy, FRAM can indeed offer an integrated approach by complementing Safety-I's more linear and proportional logic, helping to find out those aspects (potentially hazards) which would otherwise go undetected.

Safety-I's Human Factors are essential to achieve this: they are taken as a basis to describe the background, ever-present, performance variability described by Safety-II principles. The focus on Human Factors, though, is not a way to blame front-line operators, but rather is a crucial key to understand and study their continuous adaptation to the changing work situations.

Finally, it must be pointed out that variability itself is not a human error and should not be considered erroneous or destructive (therefore managed as the main condition of systemic error). Rather it must be seen as something driven by the complexity of the system's demand, rolled out on human operators with limited and fallible capabilities.

1.2.2 Essential principles

FRAM is built upon four key principles, directly derived from the Safety-II philosophy:

1. **The principle of equivalence**
   This principle states that positive and negative outcomes derive from the same causes. The same reason why things sometimes go wrong, is also the very same reason why most of the other times things go right. This is described by the *principle of approximate adjustments*.

2. **The principle of approximate adjustments**
   A socio-technical system is usually an underspecified one. This leads people to continuously adjust to the changing work conditions, varying their performance according to multiple factors (such as time, resources, etc.). Moreover, because of the underspecified nature of the system, these adjustments will always be approximate. This performance variability is the reason why the same root cause may lead to both positive and negative outcomes. Figure 1.7 shows a representation of performance variability over time: people do not perform in a dual way, like machines, but rather they operate continuously, oscillating both ways around an average value, with the ultimate aim of achieving the desired goal.

3. **The principle of emergent outcomes**
   Most of the time the variability of multiple functions combines in a way such that it produces unexpected results which cannot be explained as a result of known processes and activities (therefore called *emergent*).

4. **The principle of functional resonance**
   This principle is similar to the concept of *stochastic resonance*, where a background random noise (such as the one depicted in Figure 1.7) is always present and sometimes combines (resonates) in such a way that it pushes the output out of a certain threshold. FRAM adopts the slightly different view of *functional resonance*, based on the fact that performance variability in a socio-technical system is not completely random, since a certain regularity in the approximate adjustments people make (such as shortcuts) can be found.

Figure 1.7: Representation of the performance variability concept [13]

1.2.3 FRAM models

A FRAM analysis produces two separate models which describe the system considered, broken down in its constituent functions and describing their interdependencies. These two models represent the *"Work As Imagined (WAI)"* and the *"Work As Done (WAD)"*: the former describes the expected sequence of actions and operations as they are imagined in an ideal scenario while the latter describes the work as it is actually done, considering how activities are effectively carried out in real-life.

This shift from what is planned is due to the performance variability concept described in Section 1.2.2. By comparing the discrepancies between WAI and WAD models, one can gain valuable insights to discover where the system resilience collapsed as a result of an accumulation of variability. It is worth remembering that the WAD model refers to a specific scenario *(instantiation)* of the system, while the WAI model only describes the possible relationships or dependencies which can be generated between functions, without references to any particular situation.

Therefore, the WAD model uses only a subset of the potential couplings described by the WAI model and describes the *actual variability* of the system. The WAI model, instead, define what is known as the *potential variability*.

Each elementary function shaping the system is defined by means of six aspects [15]:

- **Input (I):** what gets transformed or processed to start the function
- **Output (O):** what is produced by the function, either an entity or a state change
- **Time (T):** temporal constraints affecting the function
- **Control (C):** what monitors and controls the function
- **Resource (R):** either what is consumed by the function to produce an output or what is needed when carried out
- **Precondition (P):** a pre-existing state or condition that must exist in order for the function to start

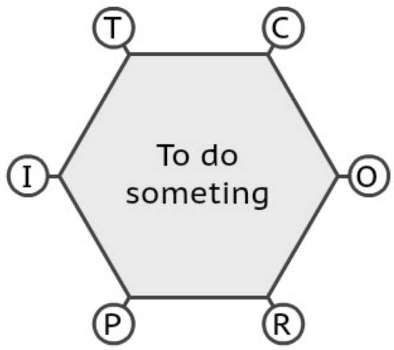


Figure 1.8: A FRAM function

Moreover, a function can be classified as:

- **Background/Foreground:** *Foreground* functions are the focus of the investigations, they can vary and they are described in more details; *Background* functions influence foreground functions and only contain either an input (sink) or output (source) without any aspect.
- **Upstream/Downstream:** a function can be classified as an *Upstream* or *Downstream* function respectively if it happens *before* or *after* another in a particular scenario

After having properly described each function and its interconnections, the WAI model can be drawn.

An in-depth explanation of the phases characterizing a FRAM analysis will be explained in Section 2 while outlining the steps followed during this project.

2 Project workflow

This Chapter describes the different Phases followed during the project, which represent the multiple steps of the proposed method of analysis, a key focus of this work.

This method was developed to provide a more structured approach to the FRAM methodology, making it easier to replicate and adaptat to various occurrences. A primary objective was to enable the possibility of tracing back the steps followed in a pragmatic and sequential way, ensuring that the final selection of Human Factors is backed by a rigorous process leading to their identification.

This approach reduces, though does not entirely eliminate, the subjectivity of the analyst, an issue which is still widely present with traditional investigation and occurrence analysis methods. By adopting this method, instead, other investigators can follow the inductive steps, confirming or refining the reasoning process without needing to infer the decisions taken, all while providing a solid base for the self-validation of the analysis, since the results can be referenced and backed by the comparison with other study cases.

Moreover, the method allows for the cross-analysis of the resulting Human Factors, helping to pinpoint the most critical underlying factors that need to be addressed with the highest priority through mitigation actions.

These goals are achieved through *five* main phases, each one corresponding to a specific task, making this method differ from a *'regular'* FRAM study. All the phases eventually lead towards the identification of commonalities and shared features among multiple occurrences, all analyzed with the FRAM methodology.

Phases 0 and 1 lay the foundations for the following phases, gathering the necessary data and selecting the events used during the comparative analysis.

Phase 2 is where the *Operative analysis* (based on FRAM) is performed and the respective results drawn. The main difference here lies in the multiple-parallel FRAM analysis conducted, focused on highlighting those aspects which will be subsequently compared, rather than aiming at drawing conclusions on each single analysis on its own, which might end up being self-validating and difficult to verify.

Moreover, a new approach to the variability propagation grading, in the WAD model building, has been introduced. Making use of a *3-level scale* instead of a traditional binary one, it has been possible to identify those functions which have contributed more (or less) to the event. The description of the grading levels is shown in Table 2.

Phase 3 and Phase 4 represent where the main innovations lie.

Phase 3 starts with the identification of the common functions among the different occurrences, which, in turn, **enables the verification of the analysis performed**. The presence of shared common functions with a comparable impact on system variability, supports the work carried out, whereas, if missing, it indicates a low reliability.

Phase 4 is where the **underlying Human Factors, affecting the common functions, are addressed and possible subsequent mitigation actions are suggested**. Through a mapping between FRAM and the traditional investigation methods, the Human Factors identified are eventually associated with their respective HFACS nanocode, whose description provides a potential mitigation action.

It is worth remembering that there is no unique way of accomplishing these tasks and some could be done differently or even skipped. This Section does not intend to provide a universal 'fixed' guide on how to conduct a FRAM analysis but rather to suggest an improved way of analyzing an occurrence and comparing it to other similar ones.

The phases are outlined in chronological order which corresponds, overall, also to the logical order of the method, although some may have been performed in parallel or even re-done at different times.

Phase 0: Definition of the purpose and framework of the analysis

Since FRAM can be used for both risk assessment and incident analysis, this phase involves the outlining of the general purpose and framework in which the project would fall within, preparing the scenario for the subsequent phases (hence the name 'Phase 0'). Based on the statistics presented in Section 1, as well as because of its specific peculiarities, the Oslo Gardermoen incident has been deemed suitable to support the fulfillment of the study's objectives and has therefore been selected as the main study case.

Phase 1: Data research

This phase involves the collection of the necessary data and its subsequent processing, in order to make it ready for the analysis. In particular:

- **Gather data**
  As much data as possible has been retrieved regarding the Oslo incident and the related entities (Airline, ATS, Airport Operator). This has included contacting the organizations directly involved (unfortunately without success) and translating the HSLB official report to Italian (Annex 1). Researches have also been carried out to

look for previous works regarding this event.
Then, other occurrences, similar to Oslo's, have been searched.
This task has been carried out by collecting data from multiple online platforms and national investigation agencies [1][2].

- **Analyze data and select similar occurrences**
  The data retrieved has been analyzed to find those occurrences which presented similar features, adequate to be compared. Two more cases have therefore been selected belonging to the CFIT category, namely the Cagliari Elmas (OE-FAN) and Narsarsuaq (D-CBNA) accidents.

- **Build occurrences database for comparison**
  The data regarding the selected occurrences has been inserted in a spreadsheet for easy access and quick cross-comparison of the main features during the selection.

Phase 2: Operative analysis (based on FRAM)

This phase represents the start of the operative FRAM analysis. The steps here described have been carried out for each of the three occurrences analyzed but could, in theory, be carried out n^{th} times, according to the number of study cases selected in Phase 1.

- **STEP 1: Functions identification**

  Step 1 is the first step to be performed in a FRAM analysis and involves the identification and classification of the system's elementary functions.

  - **Identify the essential functions of the system**
    By studying the data gathered, the aim is to identify the essential functions that enable the system to operate. This procedure has been initially done with a brainstorming activity and then optimized by reordering the list of functions while cross-checking with the timeline of the event to eventually produce a preliminary set of elementary necessary functions.

  - **Classify into macrocategories**
    The functions have been assigned to the different macrocategories that interact in the system. These are specific to each system and can be changed for each particular occurrence. Four different macrocategories have been utilized: *CREW* (green, code C.XX), *ON-BOARD SYSTEMS* (purple, code S.XX), *ATC* (blue, code ATC.XX), *AERODROME* (grey, code AD.XX). Such classification has been found useful to highlight the complexity of the system but can be omitted for simple study cases.

- **STEP 2: WAI Model development**

  After having identified the necessary functions, the WAI model can be drawn. This phase might be particularly lengthy, as it laids out the foundations of the model on which the subsequent analysis will be performed, therefore requiring particular attention and multiple validations. The tasks performed have been:

  - **Identify the interconnections between functions**
    The functions have been studied in pairs to understand whether a connection could be established through the six describing aspects, aiming at representing the relationships between them.

  - **Create the model on FMV**
    The model has been drawn using the FRAM Model Visualizer (FMV) software, representing each function and the interconnections found. This represented the first WAI model.

  - **Validate and reduce**
    This task consisted of validating the preliminary WAI model, testing its ability to fully represent the system and correctly produce the intended interconnections. This task has been carried out with the 'animate' function of the software but, above all, with the precious help of T.Col. Antonio Schifano, who provided insightful information about procedures and piloting techniques, validating and enriching the model from an operative point of view. Eventually, some functions have been discovered to be contributing less to the overall system and have then been removed. A *reduced WAI model* has therefore been produced.

These steps have been carried on multiple times, updating the model after each iteration, in order to find out the best compromise between accuracy and number of functions (loop arrow in Diagram 2.1).

This is due to the inherent nature of the model which makes it grow exponentially with each function added, therefore strongly increasing its complexity hence the difficulty in properly analysing it.

Of course, an excessive reduction would compromise the key ability of FRAM to describe all those aspects which would otherwise go undetected, therefore this activity must be carried out with caution.

- **STEP 3: WAD Model development**

  This step involves the study of the performance variability initially of the singles functions and subsequently of its propagation through the system, combining in the so-called aggregated variability. These steps have been called 3A and 3B.

  - **STEP 3A: Identification of variability**

    The tasks involved in this step address the variability of the single function and how it may be affected by internal and external factors.

    At first, each function has been classified according to its *type* with respect to variability (*Human, Organizational and Technological*). Such categorization is important as each type implies different variability oscillation characteristics (amplitude/frequency).

    Then, *external variability* has been addressed. A *Common Performance Condition (CPC)* has been assigned and rated for each function according to its applicability to the specific type. Based on the rating appointed to the CPC, the relative function could manifest a different likelihood of performance variability.

    Finally, *internal variability* has been addressed and the output of each function has been evaluated in terms of *Time and Precision*. A certain rating is more or less likely according to the type of function.

  - **STEP 3B: Aggregated variability**

    The tasks involved in this step address the propagation of variability throughout the system via the multiple interconnections established among them.

    With the help of an Excel table, each function with a varying output has been analyzed studying the connections with its downstream functions and the way such output would affect them.

    A rating was then assigned to the coupling and the propagation level determined. Traditionally, this level only addresses whether the variability amplified or dampened through the connection (therefore only assigning a '+/=/-' to indicate amplification, no effect or dampening respectively).

    Despite being of practical use, this grading has been judged to be reductive since it does not show how different functions may have contributed differently to the propagation of variability.

Therefore, a grading scale on 3 symmetric levels (3 for amplification and 3 for dampening) has been introduced. The description of the different levels is shown in Table 2.

Variability level	**Amplifying (+)**	**Dampening (-)**
Low 1	The function introduces low variability. The impact on the system is mild and its overall handling remains acceptable.	The function marginally dampens system's variability. The effects on the system are beneficial but small and cannot completely restore its safety.
Medium 2	The functions introduces considerable variability. Unpredictable elements may arise. The overall stability of the system is impacted but not compromised.	The function considerably dampens system's variability. The effects are relevant and system's stability may be restored within margins.
High 3	The function introduces high variability. Unpredictable elements are vastly present. The system is critically impacted and the effects are severe; its safety is endangered and the risk of serious incident is high.	The function highly dampens system's variability. System's stability is restored within margins and divergence is prevented. Safety is strengthen and major occurrences are avoided.

Table 2: 3-level variability propagation scale

Phase 3: Comparison & Validation of the results

This phase represent the *main innovation introduced by the method* and corresponds to the first *post-processing* step performed on the results obtained during the FRAM analysis of the different study cases.

Aggregated tables are produced, helping to pinpoint shared features and commonalities across them, in order to find out wether the analysis conducted can be supported by the other cases.

Therefore, this phase reduces the risk of self-referentiality, which is a common issue in traditional FRAM analysis, where the results obtained are often difficult to validate.

In particular the tasks performed have been:

- **Compare the occurrences**
  The occurrences have been analyzed by making aggregated tables with the most significant data and results so that the subsequent comparative analysis could be performed.

- **Identify commonalities**
  The aggregated tables have then been analyzed to pinpoint shared common functions, highlighting those that revealed to be recurrent among the study cases. It is important to take into consideration that some functions may refer to the same task but may have been assigned different names, despite being highly advisable to make them match during the WAI model development phase.

  Moreover, the variability propagation level assigned to each of them in the different occurrences has been compared, and an *average propagation index* has been computed. This is merely the arithmetic average of the values, considering positive values for amplification and negative for dampening (i.e., a value of *High 3+* was considered +3 and a value of *Low 1-* was considered -1 in the formula).

  Such a simple index enables the identification of the most critical functions, detecting those having, on average, a higher (or lower) impact on the system, and allowing for further targeted considerations.

- **Validate the analysis**
  With the results obtained after the cross-comparison carried out, the analysis performed can be validated. Although every occurrence represents a unique event, with its own characteristics and features, the presence of shared common functions, with a comparable impact on system variability may be seen as a validation of the work done, where, instead, the total lack of similar features might signal a warning of some mistakes.

Phase 4: Comparative analysis & Mitigations

This last phase represents the second *post-processing* step performed, expanding the capabilities of the method by introducing more aggregated tables for data analysis and linking FRAM with Human Factors.

This new phase allows for the identification of underlying common elements and the subsequent categorization of the associated function, according to the criticality level detected.

Indeed, in this last phase the Human Factors affecting the shared functions are addressed and possible subsequent mitigation actions are suggested. In particular:

- **Identify common Human Factors contributing to variability**
  The potential Human Factors influencing those functions having at least one CPC rated as 'Inadequate' or 'Unpredictable' have been selected. This process was based on the CPC - SHELL HF mapping developed in parallel to this project.

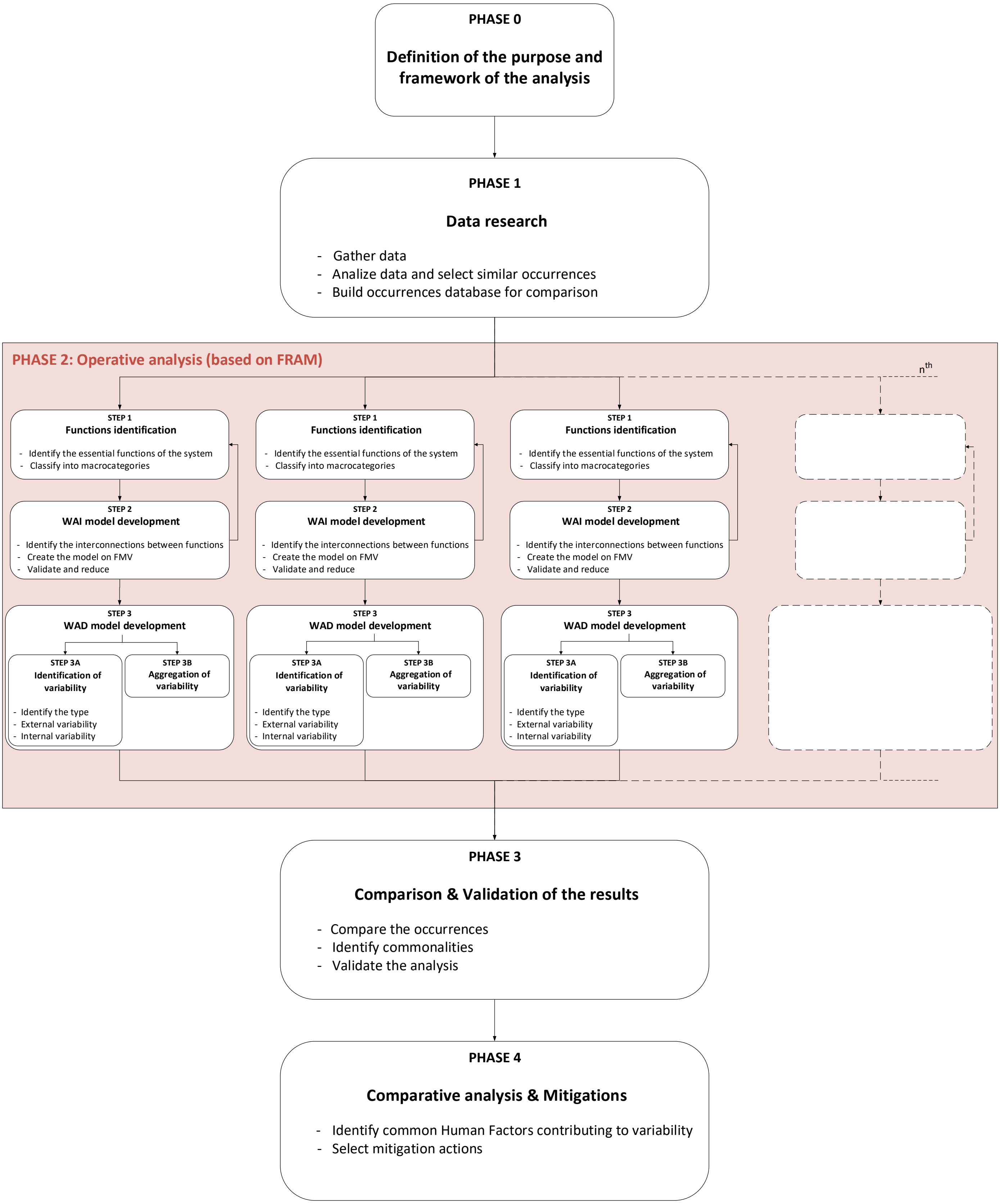
  Subsequently, further aggregated tables have been produced.

  At first, the CPCs of the common human functions have been compared so to pinpoint those functions sharing the same CPC through the different study cases.

  Next the Human Factors associated to these CPCs, in each occurrence, have been reported and compared. This has allowed for the identification of those crucial underlying elements which may be frequently present in the particular scenario considered, therefore defining themselves as the ones requiring the highest attention.

- **Select mitigation actions**
  Through the SHELL HF - HFACS mapping at our disposal, the Human Factors previously identified have been associated with their respective HFACS nanocode. The description of such nanocodes has been proposed as a potential mitigation, exploiting the HFACS taxonomy as a source of generally accepted recommendations.

2.1 Workflow diagram



3 FRAM model of the Oslo Gardermoen incident (LN-KKL)

This Chapter describes the FRAM analysis conducted regarding the incident main focus of this project, involving a Boeing 737-36N registration LN-KKL occurred on February, 9th 2003 at 13:43 UTC while operating the scheduled flight NAX541 from Stavanger Sola (ENZV) to Oslo Gardermoen (ENGM).

Section 3.1 presents a brief summary of the event, while Sections 3.2 to 3.4 outline the steps followed during the work. All the factual information have been taken from official sources, namely the HSLB report n. 20/2004 [17] and the Technical Report by Aviation Solution [9].

Figure 3.1: LN-KKL at Geneva International Airport (© Peter Leu 2012, Airfleet.net)

3.1 Description of the event

During the approach phase, under adverse weather conditions, the aircraft was being vectored by Oslo Approach for runway 19R which was in use at the time. After being authorized to descent to 4.000ft on base-leg, the controller informed the crew that de-snowing operations were being carried out on 19R and therefore the runway was closed.

Accordingly, the APP controller planned a new landing sequence that involved the re-positioning of NAX541, together with other two incoming flights, to a final heading for runway 19L, to give time at the aerodrome personnel to complete the procedures. NAX541 was therefore vectored for the new runway and cleared to intercept the ILS RWY19L (Figure 3.3).

The flight crew proceeded to prepare the aircraft appropriately, setting flaps, go-around altitude, ILS frequencies and the other necessary parameters. Shortly after the aircraft was established on the ILS path, the APP controller initiated the handoff procedure, instructing the crew to switch frequencies and contact Oslo Tower.

Nineteen seconds after the aircraft was handed over, the ground Glide Slope (GS) transmitter shut off and the signal was lost, due to an abnormal value registered by the monitoring system. Immediately after the failure, the Autopilot (AP) disconnected and the aircraft's descent rate increased to 2,200 ft/min while it was manually flown toward the ILS minimum.

Both pilots stated that no flag was displayed in the cockpit and they were only able to spot the malfunction because of unreliable data displayed on the EFIS, noticing that the GS indicator oscillated slightly before disappearing.

Moreover, the handoff procedure was not conducted according to the standards: the crew did not read back the APP instruction to contact the TWR controller and delayed the switch of frequencies by approximately 30s. The TWR controller, despite having accepted the responsability of the aircraft, did not confirm the presence of the crew on its frequency by trying to establish a radio contact with them, after not being called at.

At approximately 5 NM DME the Captain commanded a go-around as the A/C was still in dense clouds and a visual contact with the runway could not be established.

Subsequently, a new approach and eventually landing were carried out without further inconveniences.

During the first approach, the aircraft descended significantly below the expected profile and, at its lowest point, was only 460 ft AGL at 4.8 NM DME (Figure 3.2).

The investigation conducted by the HSLB [17] highlighted the fact that the crew did not perceive the aircraft's movements as abnormal during the approach sequence; this was worsened by the GS signal status information presented in a non-optimal manner and by a GPWS system that proved to be vulnerable to such situations. Furthermore, the inadequate handoff procedure between the APP and TWR controllers compromised the crew's full situational awareness.

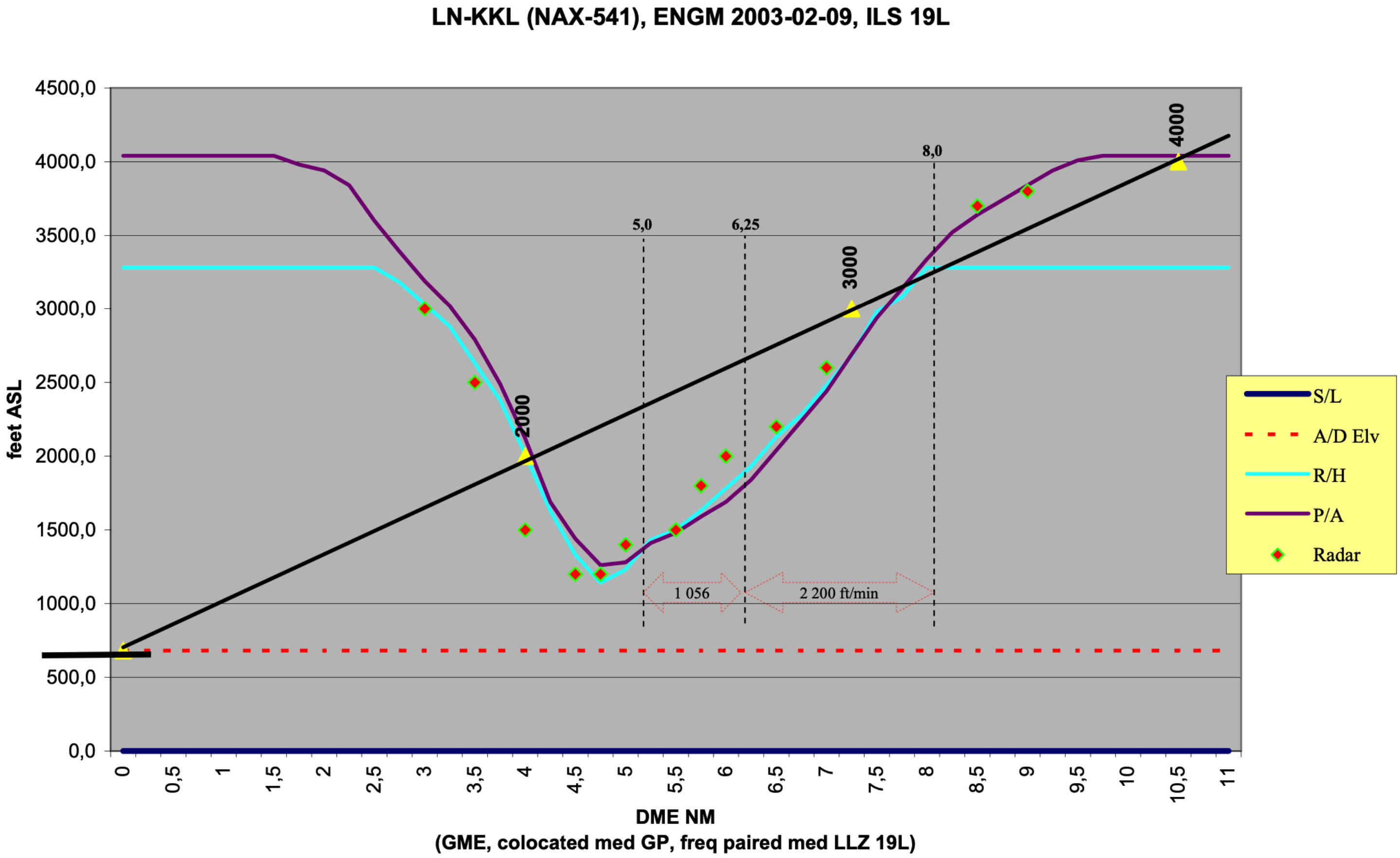


Figure 3.2: LN-KKL approach path to RWY 19L (source: [9])

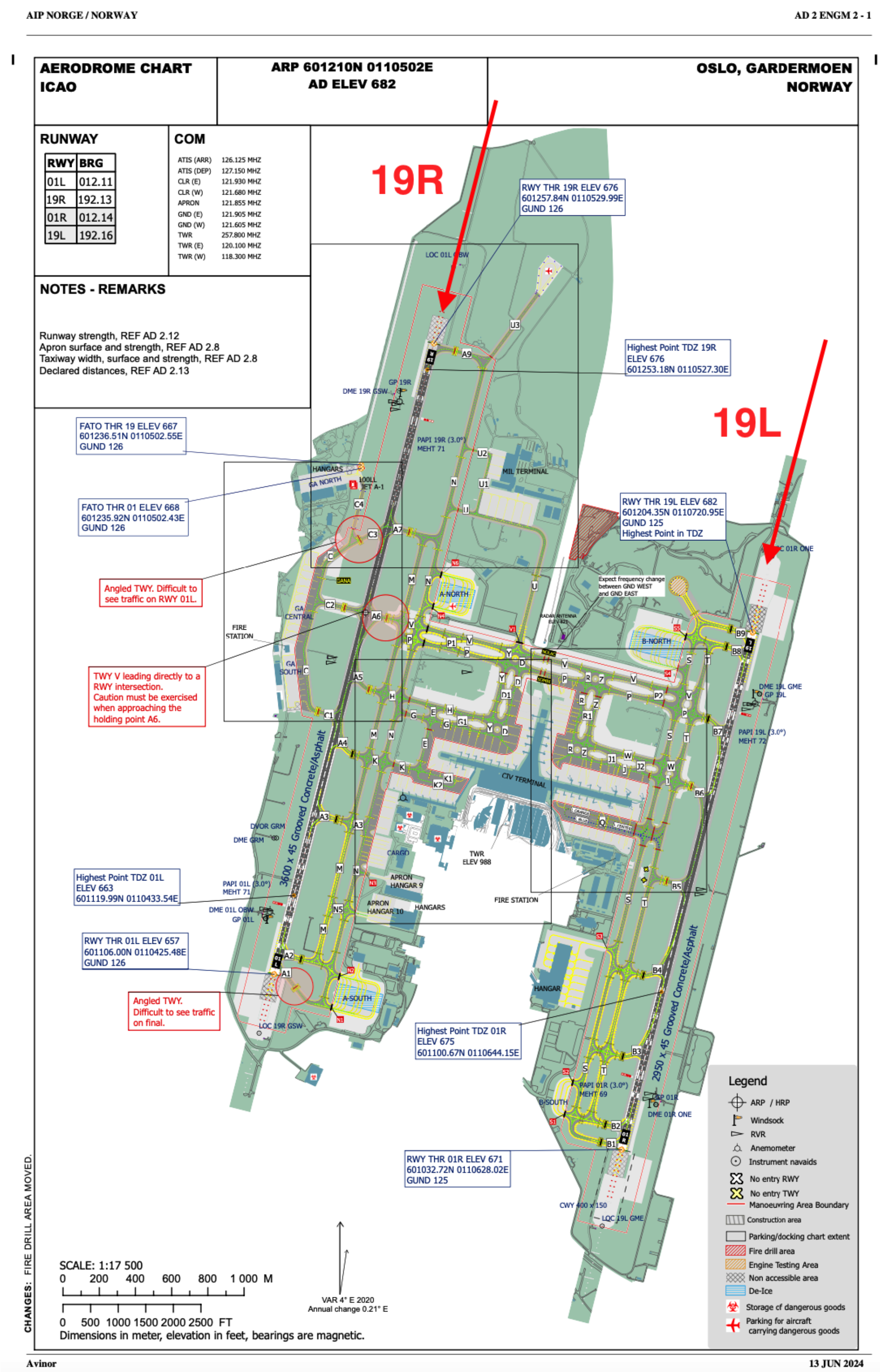


Figure 3.3: Oslo Gardermoen (EGLL) aerodrome chart (source: [10])

3.2 Functions identification

The functions identified to model this occurence are presented in Table 3. For each function the relative macrocateogry (as explained in Section 2) and its kind have been specified (B = Background, F = Foreground).

All the acronyms and symbols used are explained in the *Acronyms* section.

It is important to point out that the preliminary set of functions has been later updated during the iterations performed during the WAI model building process, as explained in Section 2 (Phase 2). Eventually, 18 functions have been identified, 5 Background and 13 Foreground.

ID	Name	Cat	B/F
AD1	Monitor AD weather	AD	B
AD2	ILS turned on	AD	B
AD3	Transmit LOC and GS signals	AD	F
ATC1	Accept incoming A/C	ATC	B
ATC2	Plan the sequence and give ILS clearance	ATC	F
ATC3	Hand over the A/C to TWR	ATC	F
ATC4	Confirm A/C is on TWR frequency	ATC	F
ATC5	Give landing clearance	ATC	F
C1	Retrieve APP charts	C	B
C2	Make approach briefing	C	F
C3	Prepare the A/C for landing	C	F
C4	Monitor approach path	C	F
C5	Switch to TWR frequency	C	F
C6	Establish visual contact with the runway	C	F
C7	Manually fly the A/C	C	F
C8	Land safely	C	B
S1	Capture and fly following ILS signals	S	F
S2	Monitor signals and terrain	S	F

Table 3: Functions identified for modelling the LN-KKL incident

3.3 WAI Model

With the functions previously identified, the WAI model realtive to this occcurence has been built. Due to the nature of the event, the model describes the *imagined* sequence of actions leading to a successful touchdown and landing on the expected runway, while any deviation from this outcome (namely both a go-around and a terrain collision) are considered instantiations and can be modeled as WAD.

Both the *initial* and the final *reduced* WAI models are presented, as a result of the *validate and reduce* step described in Section 2 (Phase 2). It can be seen that some names of functions and aspects have also been modified between the two version: this was done to better highlight the task performed by the function and to enhance the portability on other models.

The following textual description refers to the *reduced* WAI (Figure 3.5).

1. Initial descent and planning (system activation)

Ground AD personnel performs weather observations producing METAR bulletins and plans de-snowing operations including them in specific NOTAMS. Both reports are accessible by the flight crew and ATC controllers (**AD.1. Monitor AD weather)**. The APP controller plans the arrival sequence with respect to these infromation and the incoming A/Cs received from a previous APP (or Enroute) controller (**ATC.1. Accept incoming A/C)**, authorizing the crew to intercept the ILS accordingly (**ATC.2. Plan the sequence and give ILS clearance)**.

Name of function	AD.1. Monitor AD weather
Description	AD personnel make continuous weather observations producing a METAR bulletin to anticipate risks affecting the approach and landing phases and plan for runway sweeping operations (including de-snowing)
Aspect	**Description of Aspect**
Input	
Output	METAR and SNOWTAM bulletin
Precondition	
Resource	
Control	
Time	

Function <AD.1. Monitor AD weather>

Name of function	ATC.1. Accept incoming A/C
Description	The APP controller receives the A/C from an en-route controller or another APP controller assuming the responsability over it
Aspect	**Description of Aspect**
Input	
Output	Incoming A/C accepted
Precondition	
Resource	
Control	
Time	

Function <ATC.1. Accept incoming A/C>

Name of function	ATC.2. Plan the sequence and give ILS clearance
Description	The APP controller outlines a landing sequence, informing the crew of the expected runway and giving ILS clearance according to traffic prioritization
Aspect	**Description of Aspect**
Input	METAR and SNOWTAM bulletin
	Incoming A/C accepted
Output	Crew informed of expected runway
	ILS clearance given
Precondition	
Resource	
Control	
Time	

Function <ATC.2. Plan the sequence and give ILS clearance>

2. Approach preparation

After having received weather information, NOTAMS and the expected landing runway, pilots retrieve the proper approach charts (**C.1. Retrieve APP charts)** and proceed to make a briefing on the upcoming phase, discussing important features such as minimums, restrictions and go-around altitudes and preparing for the eventuality of a runway change or a degradation to a non-precision approach **(C.2. Make approach briefing)**.

Name of function	C.1. Retrieve APP charts
Description	The flight crew retrieves the necessary approach charts and put them close at hand in order to be easily accessed when needed
Aspect	**Description of Aspect**
Input	
Output	APP charts at hand
Precondition	
Resource	
Control	
Time	

Function <C.1. Retrieve APP charts>

Name of function	C.2. Make approach briefing
Description	The flight crew reviews the approach procedures, highlighting important features (minimums, restrictions, etc.) and preparing to adopt contingency measures if needed
Aspect	**Description of Aspect**
Input	METAR and SNOWTAM bulletin
	Crew informed of expected runway
Output	Crew ready for the approach
Precondition	
Resource	APP charts at hand
Control	
Time	

Function <C.2. Make approach briefing>

Then, the crew prepares the aircraft for landing, setting flaps, speedbrakes, autobrakes, FCU, etc. and tuning the NAV frequency on the ILS of the expected runway. Only after having received the clearance from the APP controller to intercept the ILS course, the crew can arm the APPR mode, which makes the A/C scan for the LOC and GS signals transmitted from the AD (**C.3. Prepare the A/C for landing)**. Specifically, these signals are broadcasted from antennas **(AD.3. Transmit LOC and GS signals)** integrated in a broader operative ground system of infrastructures **(AD.2. ILS turned on)**.

Name of function	C.3. Prepare the A/C for landing
Description	The flight crew sets the A/C for landing (flaps, speedbrakes, FMS etc.), tune the ILS frequency and arm the APPR button when authorized by the APP controller
Aspect	Description of Aspect
Input	Crew ready for the approach
Output	ILS frequency set and APPR armed
	A/C ready for the approach
Precondition	ILS clearance given
Resource	
Control	
Time	

Function <C.3. Prepare the A/C for landing>

Name of function	AD.2. ILS turned on
Description	The Instrument Landing System (ILS) is activated to provide LOC and GS signals for approach navigation
Aspect	Description of Aspect
Input	
Output	ILS properly working
Precondition	
Resource	
Control	
Time	

Function <AD.2. ILS turned on>

Name of function	AD.3. Transmit LOC and GS signals
Description	The Localizer (LOC) and Glide Slope (GS) signals are transmitted through the system's antennas to provide aircraft with approach path guidance
Aspect	Description of Aspect
Input	ILS properly working
Output	Signals transmitted
Precondition	
Resource	
Control	
Time	

Function <AD.3. Transmit LOC and GS signals>

3. Final approach and landing

Once the A/C is in APPR mode, the avionic system captures the ILS signals and start tracking them, enabling the Flight Director to establish the A/C on the ILS path. **(S.1. Capture and fly following ILS signals)**. This function is therefore the one describing the automatic flight performed by the autopilot. Subsequently, after a visual contact with the runway has been established **(C.6. Establish visual contact with the runway)**, the Pilot Flying (PF) takes over the control of the A/C and manually flies it **(C.7. Manually fly the A/C)** to a safe touchdown and a complete stop **(C.8. Land safely)**. Thus, function C.6 describes the manual flight phase.

Name of function	S.1. Capture and fly following ILS signals
Description	The aircraft locks onto and follows the ILS signals, ensuring a precise approach to the runway
Aspect	Description of Aspect
Input	Signals transmitted
Output	A/C established and stable on the ILS
Precondition	ILS frequency set and APPR armed
Resource	Signals monitored
Control	Approach path monitored
Time	

Function <S.1. Capture and fly following ILS signals>

Name of function	C.6. Establish visual contact with the runway
Description	The flight crew looks outside the windshield to establish a visual contact with the runway before the minimum altitude is reached
Aspect	Description of Aspect
Input	A/C established and stable on the ILS
Output	Runway in sight
Precondition	
Resource	
Control	
Time	

Function <C.6. Establish visual contact with the runway>

Name of function	C.7. Manually fly the A/C
Description	The Pilot Flying (PF) takes over the control of the A/C and manually flies the remaining part of the approach and landing, if and when the proper operational conditions are met
Aspect	Description of Aspect
Input	Runway in sight
Output	A/C manually flown
Precondition	Landing clearance given
Resource	Flags and alarms in the cockpit
Control	Approach path monitored
	TWR frequency monitored
Time	

Function <C.7. Manually fly the A/C>

Name of function	C.8. Land safely
Description	The landing sequence si completed and the A/C performs a safe touchdown on the runway
Aspect	Description of Aspect
Input	A/C manually flown
Output	
Precondition	
Resource	
Control	
Time	

Function <C.8. Land safely>

4. Control over the approach

Both the automatic and manual flight functions (S.1 and C.7) are performed under the rigorous surveillance of the crew, who monitors the descent along the approach path. This includes comparing the A/C altitude and distance with respect to the one drawn in the APP charts, as well as checking the speed and the external environment, assessing the surrounding terrain, nearby traffic and meteorological factors **(C.4. Monitor approach path)**. Meanwhile, on-board avionics monitors the integrity of the signals received from the ILS antennas (disconnecting the AP in case of malfunctions), the terrain and its topography, the sink rate and other flight parameters differing in every specific model of GPWS. This system is capable of generating flags and aural alarms in the cockpit to alert both pilots, increasing their situational awareness **(S.2. Monitor signals and terrain)**.

Name of function	C.4. Monitor approach path
Description	The flight crew monitors the A/C's descend path, checking the correspondace with the designated one and verifying the separation from terrain obstacles and nearby traffic
Aspect	**Description of Aspect**
Input	A/C ready for the approach
	Crew ready for the approach
Output	Approach path monitored
Precondition	
Resource	APP charts at hand
Control	
Time	

Function <C.4. Monitor approach path>

Name of function	S.2. Monitor signals and terrain
Description	The avionic system monitors the integrity of the ILS signals received and the terrain ahead, generating flags and alarms in the cockpit to alert the crew and disconnecting the AP if needed
Aspect	**Description of Aspect**
Input	Signals transmitted
Output	Signals monitored
	Flags and alarms in the cockpit
Precondition	
Resource	
Control	
Time	

Function <S.2. Monitor signals and terrain>

5. Handoff procedure

The handoff sequence between the APP and TWR controller starts after the crew has reported established on the ILS **(ATC.3. Hand over the A/C to TWR)**. After having accepted the responsibility over the A/C, the TWR controller must verify the crew has properly carried out the frequency switch, establishing a radio contact with the pilots in case they do not check in promptly on the frequency **(ATC.4. Confirm A/C is on TWR frequency)**. After the switch **(C.5. Switch to TWR frequency)**, the flight crew monitors the communications in order to spot important aspects affecting the safety and operativity of their flight. The TWR controller eventually clears the A/C to land when the appropriate conditions are met **(ATC.5. Give landing clearance)**.

Name of function	ATC.3. Hand over the A/C to TWR
Description	The APP controller initiates the handoff procedure transferring the responsability for the A/C to the TWR controller
Aspect	Description of Aspect
Input	ILS clearance given
Output	A/C handed over
Precondition	A/C established and stable on the ILS
Resource	
Control	
Time	

Function <ATC.3. Hand over the A/C to TWR>

Name of function	ATC.4. Confirm A/C is on TWR frequency
Description	The TWR controller confirms the A/C is correctly tuned to his frequency by ensuring a proper radio contact with the flight crew has been established
Aspect	Description of Aspect
Input	A/C handed over
Output	Contact with A/C established
Precondition	
Resource	
Control	
Time	

Function <ATC.4. Confirm A/C is on TWR frequency>

Name of function	ATC.5. Give landing clearance
Description	The TWR controller clears the A/C for landing ensuring the runway is available for a safe touchdown
Aspect	**Description of Aspect**
Input	TWR frequency monitored
Output	Landing clearance given
Precondition	
Resource	
Control	
Time	

Function <ATC.5. Give landing clearance>

Name of function	C.5. Switch to TWR frequency
Description	The flight crew switches its radio frequency to TWR as soon as instructed by the APP controller during the handoff
Aspect	**Description of Aspect**
Input	A/C handed over
Output	TWR frequency monitored
Precondition	
Resource	
Control	Contact with A/C established
Time	

Function <C.5. Switch to TWR frequency>

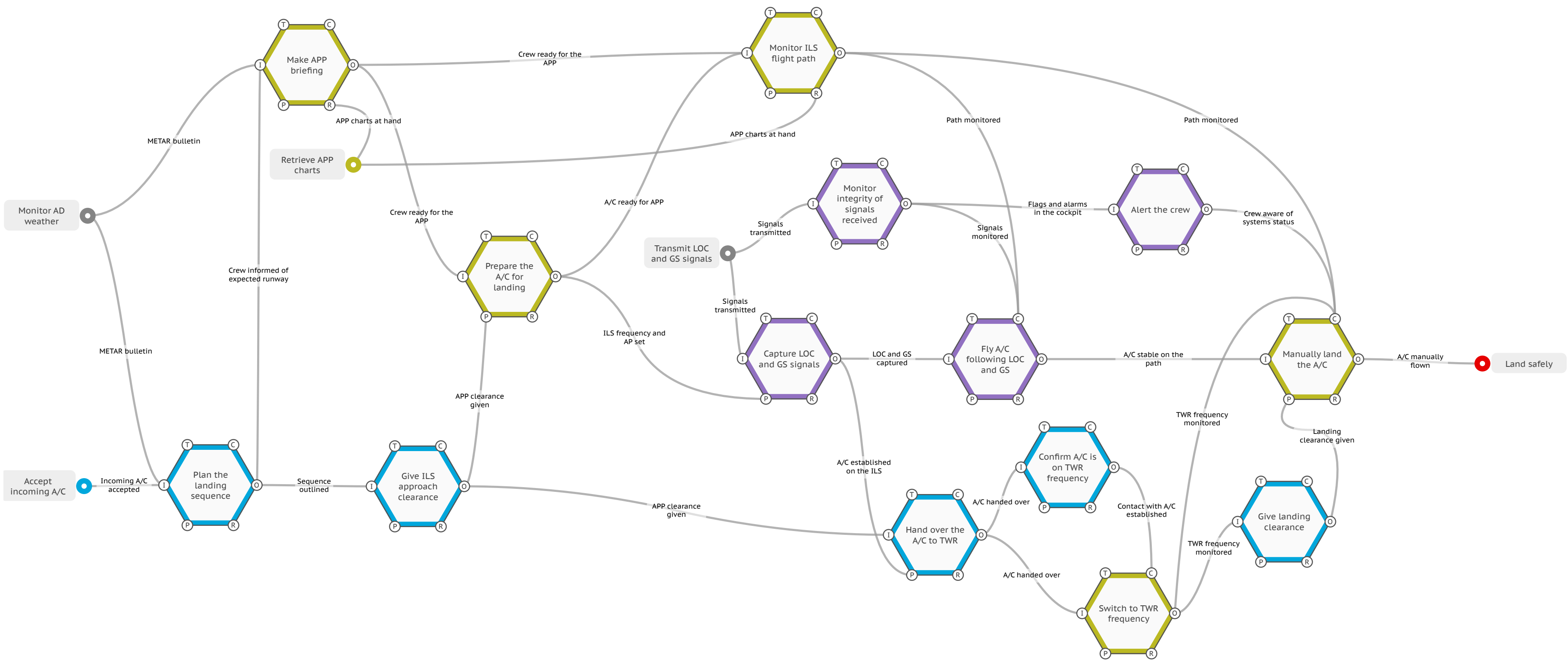


Figure 3.4: Initial WAI model of the Oslo Gardermoen incident (LN-KKL)

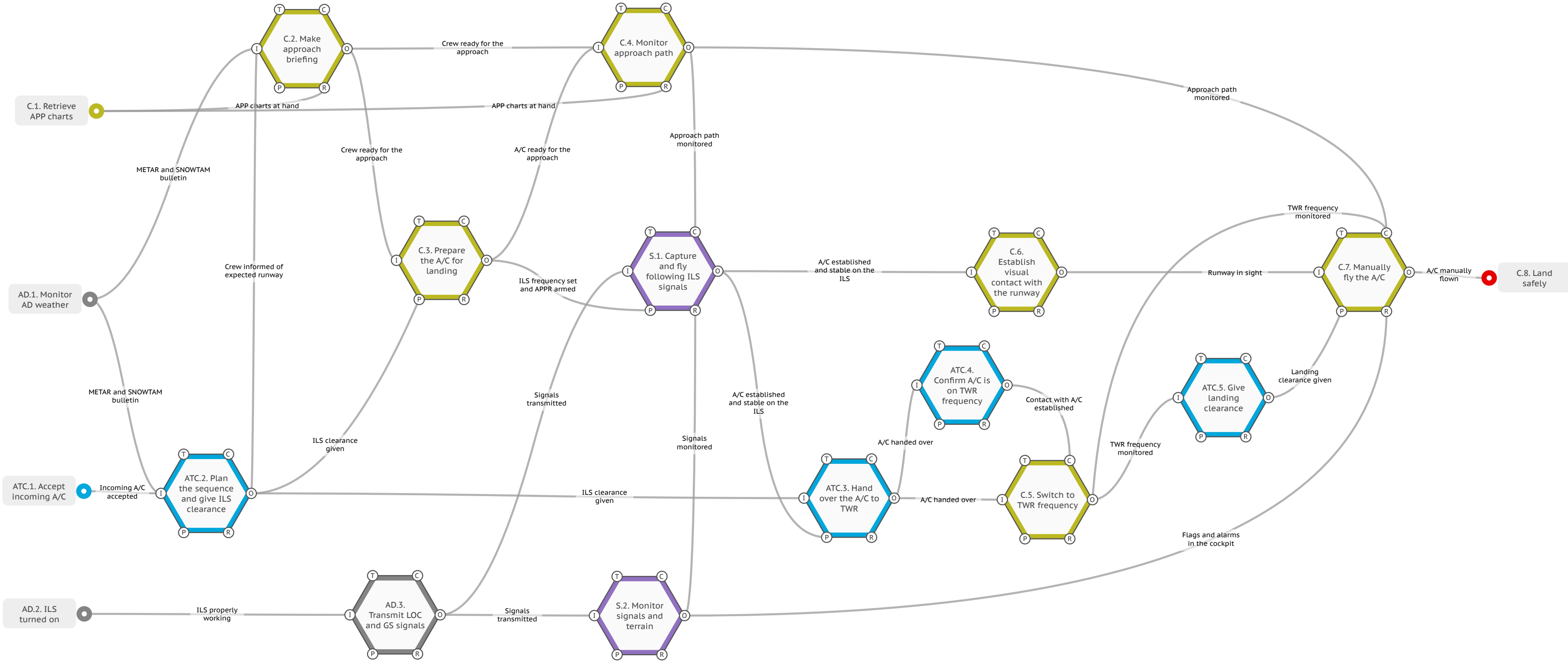


Figure 3.5: Final optimized WAI model of the Oslo Gardermoen incident (LN-KKL)

3.4 WAD Model

Variability in the system was initiated by the ground GS transmitter which shut off due to the abnormal values registered **(AD.3. Transmit LOC and GS signals)**, interrupting the couplings with the downstream functions. This happened shortly after the A/C was established on the ILS path for RWY 19L and was being flown automatically by the AP. The system correctly disconnected the AP and triggered an aural and visual alarm in the cockpit, prompting the pilots to take manual control of the A/C.

For this reason, the approach was then degraded to a *non-precision approach* in which the crew manually flies the A/C down to the new minimum: a new coupling was created between functions **(S.1. Capture and fly following ILS signals)** and **(C.7. Manually fly the A/C)** while function **(C.6. Establish visual contact with the runway)** became a control over the manual flight function.

Meanwhile, the approach path was monitored imprecisely, as the PNF believed to be closer to the runway threshold and did not rely on the DME information presented by the instruments in the cockpit, cross-checking them with the altitude/distance tables drawn in the charts **(C.4. Monitor approach path)**. Likewise, On-Board systems did not warn the crew of the GS signal malfunction since no flags or alarms relative to the signal and the terrain ahead (GPWS) set off. Moreover, the FD-mode "GS" indication remained visible with green letters on the EADI, which all contributed to degrade the situational awareness of the pilots, intriducing more variability in the system **(S.2. Monitor signals and terrain)**. Both couplings with the manual flight function were interrupted.

The handoff procedure was not carried out according to standards. When the APP controller instructed NAX541 to contact Oslo Tower, the crew did not readback the instruction and the controller assumed that they had implicitly switched to TWR without further inquiring aknowledgement **(ATC.3. Hand over the A/C to TWR)**. Instead, the crew waited approximately 30 sec. before actually switching frequency and this resulted in losing important information relayed by the TWR controller regarding the GS-inop status **(C.5. Switch to TWR frequency)**. In addition, the TWR controller accepted the handoff from Oslo APP and took responsibility for the A/C, but did not attempt to call NAX541 after not being contacted directly by the crew **(ATC.4. Confirm A/C is on TWR frequency)**.

Eventually, after noticing a small deviation on the LOC path indicator and realizing that the A/C was still flying in dense clouds without visual contact with the runway, the Captain decided to abort the approach and commanded a go-around. This introduced a *positive dampening variability* which ultimately prevented the A/C from impacting the terrain **(C.6. Establish visual contact with the runway)**.

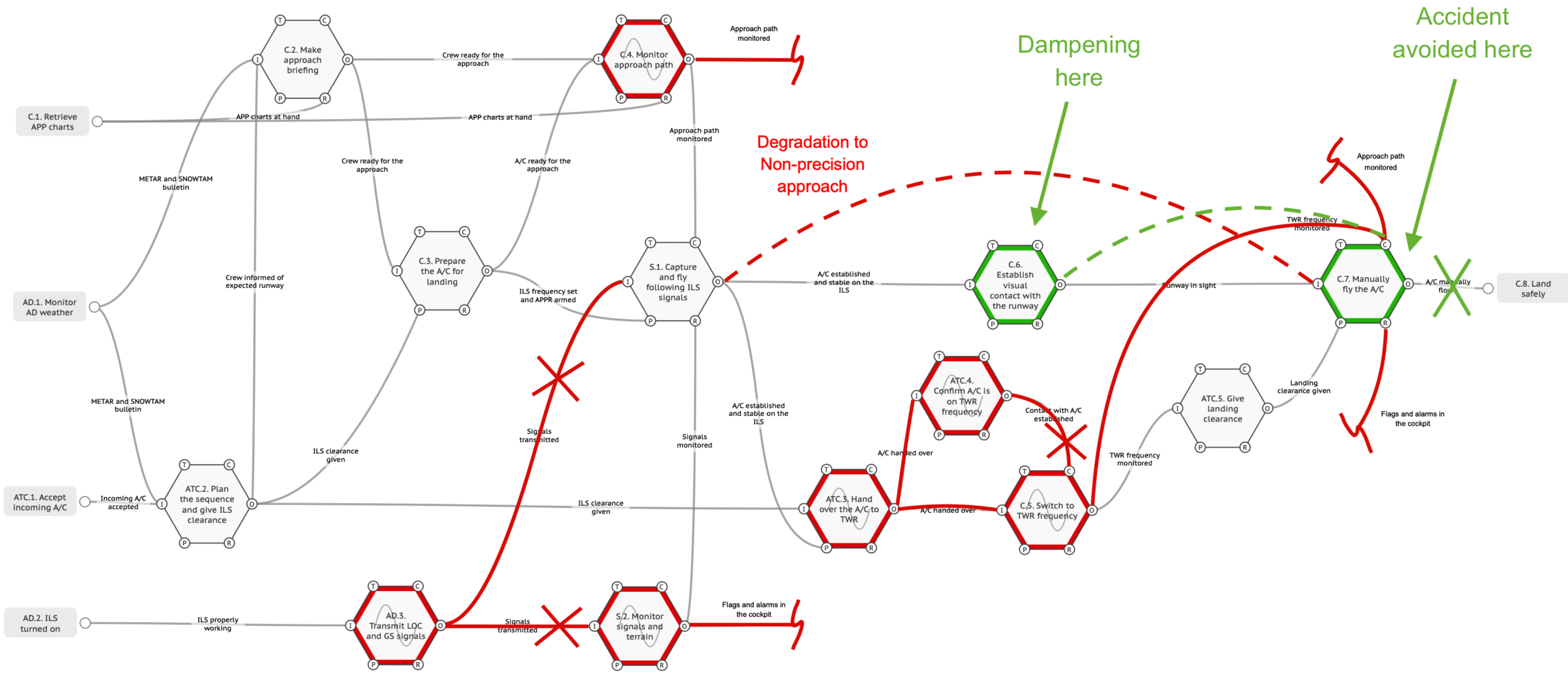


Figure 3.6: WAD model of the Oslo Gardermoen incident (LN-KKL)

Note: some interrupted couplings have been drawn as separate segments for graphical purposes

3.4.1 Type identification

The first step in the analysis of the WAD model has been the classification of the functions with respect to their type: *Organizational*, *Human* and *Technological*.

Table 4 shows the assigned type for each function.

ID	Function	Type
AD1	Monitor AD weather	Organizational
AD2	ILS turned on	Technological
AD3	Transmit LOC and GS signals	Technological
ATC1	Accept incoming A/C	Human
ATC2	Plan the sequence and give ILS clearance	Human
ATC3	Hand over the A/C to TWR	Human
ATC4	Confirm A/C is on TWR frequency	Human
ATC5	Give landing clearance	Human
C1	Retrieve APP charts	Human
C2	Make approach briefing	Human
C3	Prepare the A/C for landing	Human
C4	Monitor approach path	Human
C5	Switch to TWR frequency	Human
C6	Establish visual contact with the runway	Human
C7	Manually fly the A/C	Human
C8	Land safely	Human
S1	Capture and fly following ILS signals	Technological
S2	Monitor signals and terrain	Technological

Table 4: Functions type classification with respect to variability (LN-KKL)

It can be seen that the majority of the functions belong to the Human type, as they are perfomed by humans in small groups, namely the crew or the ATC controllers.

Function AD.1. Monitor AD weather is performed by the aerodrome ground personell, who works in team in a structured manner to produce and issue weather observations and their relative bulletins. Therefore, these have been classified as of Organizational type.

The remaining functions fall under the Technological classification as they are automatically performed by inanimate objects, such as on-boards systems, avionics and ground infrastructures without a direct human involvement.

3.4.2 External variability

Table 5 shows the assessment of the external variability and the assigned CPC only for those funtions whose rating has been marked *Inadequate*.

ID	Function	Type	Common Performance Condition	Rating	Likely performance variability
AD3	Transmit LOC and GS signals	T	Availability of resources	Inadequate	Noticeable
			Conditions of work	Adequate	Small
ATC3	Hand over the A/C to TWR	H	Quality of communication	Inadequate	Noticeable
ATC4	Confirm A/C is on TWR frequency	H	Quality of communication	Inadequate	Noticeable
			Team collaboration quality	Inadequate	Noticeable
C4	Monitor approach path	H	Adequacy of HMI and operational support	Inadequate	Noticeable
			Conditions of work	Inadequate	Noticeable
			Number of goals and conflict resolution	Inadequate	High
			Available time and time pressure	Inadequate	High
			Team collaboration quality	Inadequate	Noticeable
C5	Switch to TWR frequency	H	Quality of communication	Inadequate	Noticeable
			Available time and time pressure	Inadequate	High
C6	Establish visual contact with the runway	H	Training and experience	Adequate	Small
S2	Monitor signals and terrain	T	Availability of resources	Inadequate	Noticeable
			Conditions of work	Adequate	Small

Table 5: External variability and CPC (LN-KKL)

Functions AD.2 and S.2 have been assigned the CPC *"Availabilty of resources"* rated *Inadequate* for both. Indeed, this contemplates the loss of the GS signal transmitted and the fact that the on-board systems were inadequate to properly present the system status information to the pilots.

Functions ATC.3, ATC.4 and C.6 involve the poor standards followed during the handoff procedures and therefore the assigned CPC have been rated *Inadequate*.

Function C.4 was affected by multiple CPCs. These contemplate the inadequacy of the GS indication on the EADI, which remained green even after the loss of signal generating confusion, the nightime and bad weather conditions present as well as the pressure generated from the high workload situation. Function C.6's assigned CPC is presented in green as this was the condition that led to the dampening of variability.

3.4.3 Internal variability

Table 6 describes the assessment of the internal variability. Only functions whose rating is *Imprecise*, *Too late* or *Not at all* are shown.

ID	Name	Output	Time	Precision
AD3	Transmit LOC and GS signals	Signals transmitted	Not at all	-
ATC3	Hand over the A/C to TWR	A/C handed over	On time	Imprecise
ATC4	Confirm A/C is on TWR frequency	Contact with A/C established	Not at all	-
C4	Monitor approach path	Approach path monitored	Not at all	Imprecise
C5	Switch to TWR frequency	TWR frequency monitored	Too late	Precise
C6	Establish visual contact with the runway	Runway in sight	On time	Precise
C7	Manually fly the A/C	A/C manually flown	On time	Precise
S2	Monitor signals and terrain	Signals monitored	On time	Precise
		Flags and alarms in the cockpit	Not at all	Imprecise

Table 6: Internal variability (LN-KKL)

Functions AD.3 and ATC.3 have been rated *Not at all* since the couplings with their respective downstream functions were interrupted (i.e. did not take place in the event considered). Moreover, the handoff procedure was carried out imprecisely by the APP controller who did not further inquire a readback, while the crew switched to the right frequency but with a delay of almost 30 sec. Thus, functions ATC.4 and C.5 have been rated respectively *Imprecise* and *Too late*.

Function C.4 has been rated *Imprecise* and *Not at all* since the DME on-board instruments were not checked to verify the A/C distance with respect to the runway and no altitude calls were made. Function S.2 has been equally rated, due to the lack of alarms and flags in the cockpit and the imprecise GS indication on the EADI.

Finally, functions C.6 and C.7 have been represented in green to underline that their output contributed to the dampening of variability.

3.4.4 Aggregated variability

Table 7 represents the assessment of the aggreagated variability, considering only the couplings which contributed to its propagation.

Upstream function	Output	Variability	Downstream function		Effect	Variability propagation scale	
						+/-	3 levels
AD.3. Transmit LOC and GS signals	Signals transmitted	Not at all	I	S.1. Capture and fly following ILS signals	Function degradation Loss of accuracy	V+	High 3+
			I	S.2. Monitor signals and terrain	Function degradation Loss of accuracy	V+	Low 1+
ATC.3. Hand over the A/C to TWR	A/C handed over	On time Imprecise	I	ATC.4. Confirm A/C is on TWR frequency	Loss of accuracy	V+	Low 1+
			I	C.5. Switch to TWR frequency	Imprecise start of function	V+	Medium 2+
ATC.4. Confirm A/C is on TWR frequency	Contact with A/C established	Not at all	C	C.5. Switch to TWR frequency	Control input may be missed	V+	Medium 2+
C.4. Monitor approach path	Approach path monitored	Not at all Imprecise	C	S.1. Capture and fly following ILS signals	Control input may be missed	V=	Low 1+
			C	C.7. Manually fly the A/C	Control input may be missed	V+	High 3+
C.5. Switch to TWR frequency	TWR frequency monitored	Too late Precise	C	C.7. Manually fly the A/C	Control input may be missed	V+	High 3+
			I	ATC.5. Give landing clearance	No effect	V=	Neutral 0
C.6. Establish visual contact with the runway	Runway in sight	On time Precise	C	C.7. Manually fly the A/C	Possible dampening	V-	High Damp 3-
S.1. Capture and fly following ILS signals	A/C established and stable on the ILS	On time Precise	P	ATC.3. Hand over the A/C to TWR	No effect	V=	Neutral 0
			I	C.6. Establish visual contact with the runway	No effect	V=	Neutral 0
			I	C.7. Manually fly the A/C	Coupling created	V+	Medium 2+
S.2. Monitor signals and terrain	Signals monitored	On time Precise	R	S.1. Capture and fly following ILS signals	No effect	V=	Neutral 0
	Flags and alarms in the cockpit	Not at all Imprecise	R	C.7. Manually fly the A/C	Resource input may be missed	V+	High 3+

Table 7: Aggregated variability and couplings (LN-KKL)

Multiple functions affected their downstream functions to a *High* extent, heavily contributing to propagate the variability throughout the system:

- **Function AD.3:** highly impacted function S.1 since, when the GS signal was lost, the AP did not have a vertical plane reference point to follow. Function S.2 was less influenced since the system was designed to monitor such malfunctions.
- **Function C.4:** highly impacted function C.7 since being of paramount importace during a *non-precision* manually-flown approach. This also resulted in the interruption of the coupling. During the initial *precision* approach phase (with AP engaged) this function had a lower impact
- **Function C.5:** highly impacted function C.7 since, by delaying the frequency switch, the crew lost important information regarding the GS-inop status which degraded their situational awareness.
- **Function S.2:** highly impacted function C.7 due to the lack of flags and alarms in the cockpit as well as the sub-optimal green GS EADI indicator, which confused the crew and degraded their situational awareness

Three functions have affected their downstream functions to a *Medium* extent:

- **Functions ATC.3** and **ATC.4:** refer to the handoff procedure carried on by the APP and TWR controllers, which did not meet the required standards and introduceed variability in a critical process
- **Funtion S.1:** this coupling was created when the crew degraded the approach to *non-precision*, taking manual control over the A/C. Despite being a possibilty during an approach, this was an unexpected coupling which affected function C.7

Finally, one function has contributed to *Highly dampen* the propagation of variability in the system:

- **Function C.6:** when realizing that the A/C was still flying in dense clouds and a visual contact with the runway could not be established, a go-around was commanded. This highly dampened the variability and stopped the A/C from impacting the ground

4 FRAM model of other similar occurrences

This Chapter presents the occurrences selected for comparison among those collected during the database building process. Both belong to the CFIT category and share similar features with the Oslo Gardermoen incident. Both analyses are supported by sufficient solid data.

4.1 Cagliari Elmas accident (OE-FAN)

The event has occurred on February, 24th 2004 at 04:49 UTC involving a Cessna 500 Citation I registration OE-FAN while operating a medical flight (callsign CIT124) to transport organs for transplant, from Roma Ciampino airport (LIRA) to Cagliari Elmas airport (LIEE).

Section 4.1.1 presents a brief summary of the event. Section 4.1.2 describes the WAI model represented in Figure 4.5 while Section 4.1.3 outlines the WAD model.

All the factual information have been taken from official sources, namely the official report by ANSV and its Annexes [7].

Figure 4.1: OE-FAN at Düsseldorf Airport (© Werner Fischdick 1985, aviation-safety.net)

4.1.1 Description of the event

During the approach to Cagliari Elmas (LIEE), while overflying waypoint *ALESI*, the A/C was cleared by Cagliari APP for the ILS-P approach RWY 32 and instructed to descend to 5000 ft, reporting when passing Carbonara VOR (CAR) to start the Standard Arrival Route (STAR) procedure (Figure 4.2). The controller had previously accepted the handoff from Roma ACC.

At approximately 28 NM out, CIT124 requested clearance for a visual approach for runway 32. Upon request by the controller, the crew reported when they had the field in sight and confirmed able to maintain visual separation from obstacles. Consequently, the initial clearance was amended and the flight crew was re-cleared for a visual approach, while being instructed to descend not below 2500 ft.

At the same time the controller coordinated via thelephone with Elmas TWR and initiated the handoff procedure, transferring responsibility and advising the A/C to switch frequency.

Shortly after having been cleared for landing, the A/C impacted the mountainous terrain situated approximately 18 NM Est of the destination aerodrome, at the summit of mount Su Baccu Malu (3333 ft). The path followed is plotted in Figure 4.3 and 4.4.

All the occupants lost their lives and the A/C got completely destroyed.

The investigation pointed out how the main contributing factors were mainly linked to human factors: erroneous visual clues taken by the pilots, confused with the runway lights, probably worsened by the visual illusion known as *"Black hole effect"*. Moreover, fatigue and the premature deviation from the approach route, maybe due to the medical nature of the flight, might have had a significant effect.

Finally, the absence of a GPWS on-board, permitted by the legislation of the time for such class of aircraft, as well as a possible miscommunication between the pilots and controller have been considered non-negligible by the investigators.

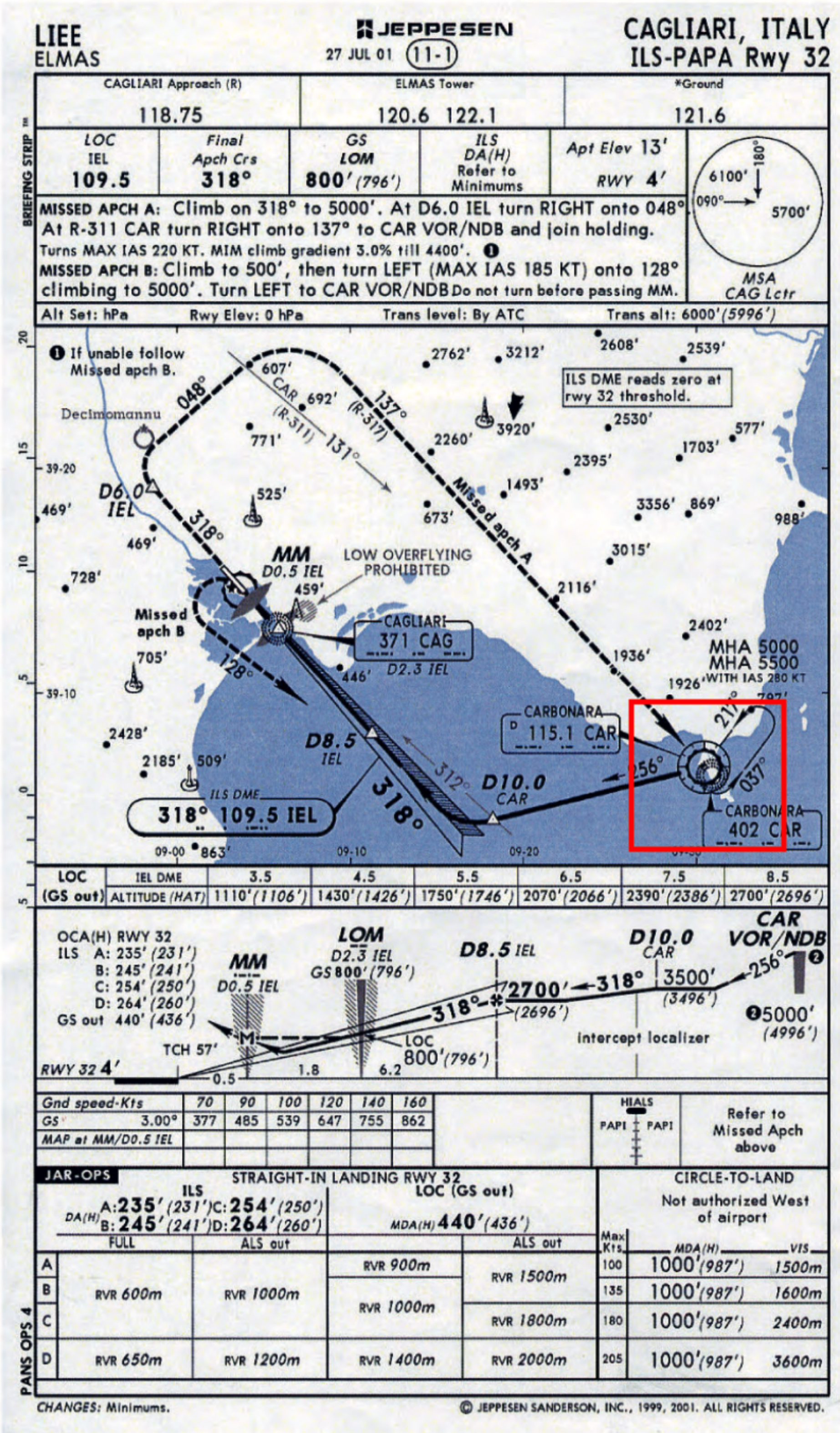


Figure 4.2: ILS-P RWY32 Jeppesen chart (CAR VOR highlighted)

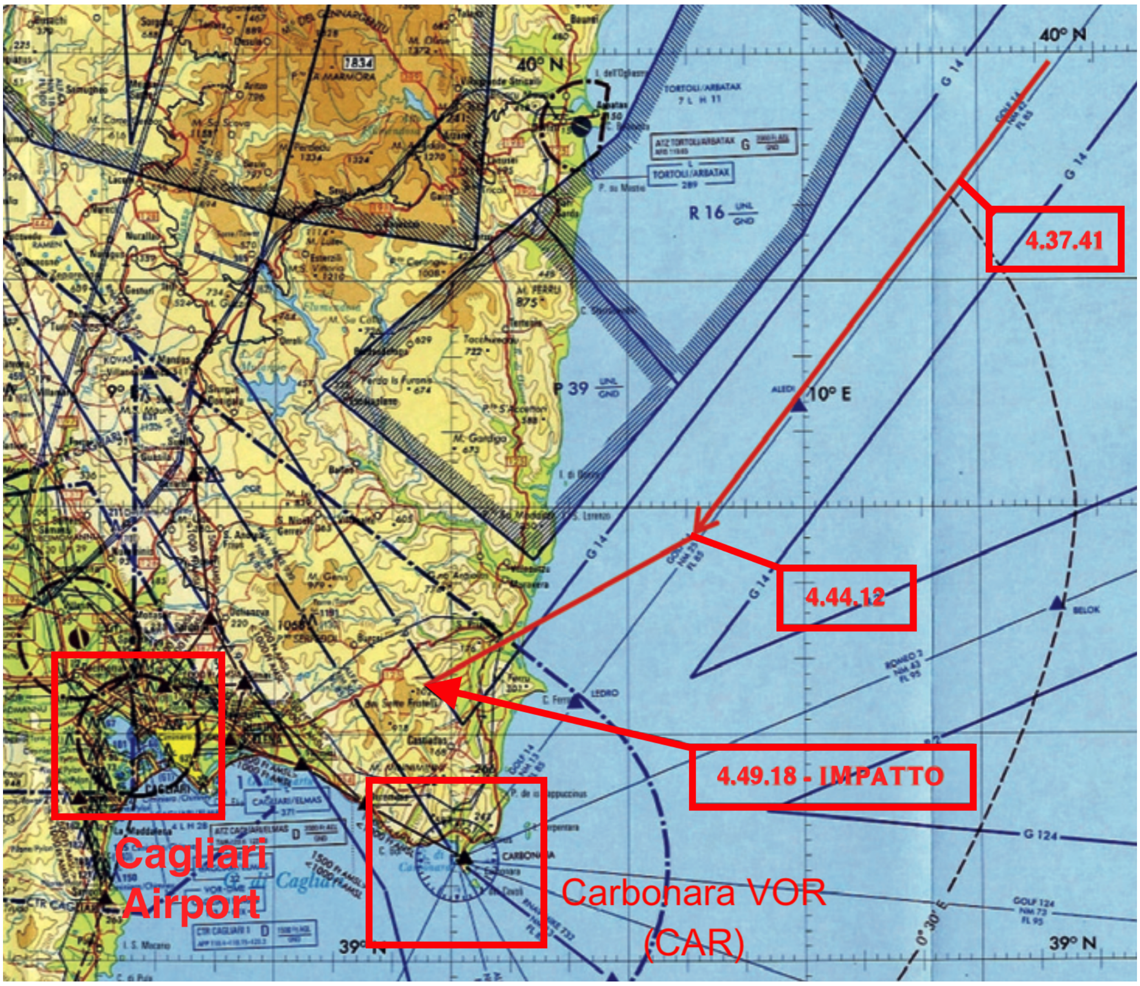


Figure 4.3: OE-FAN track

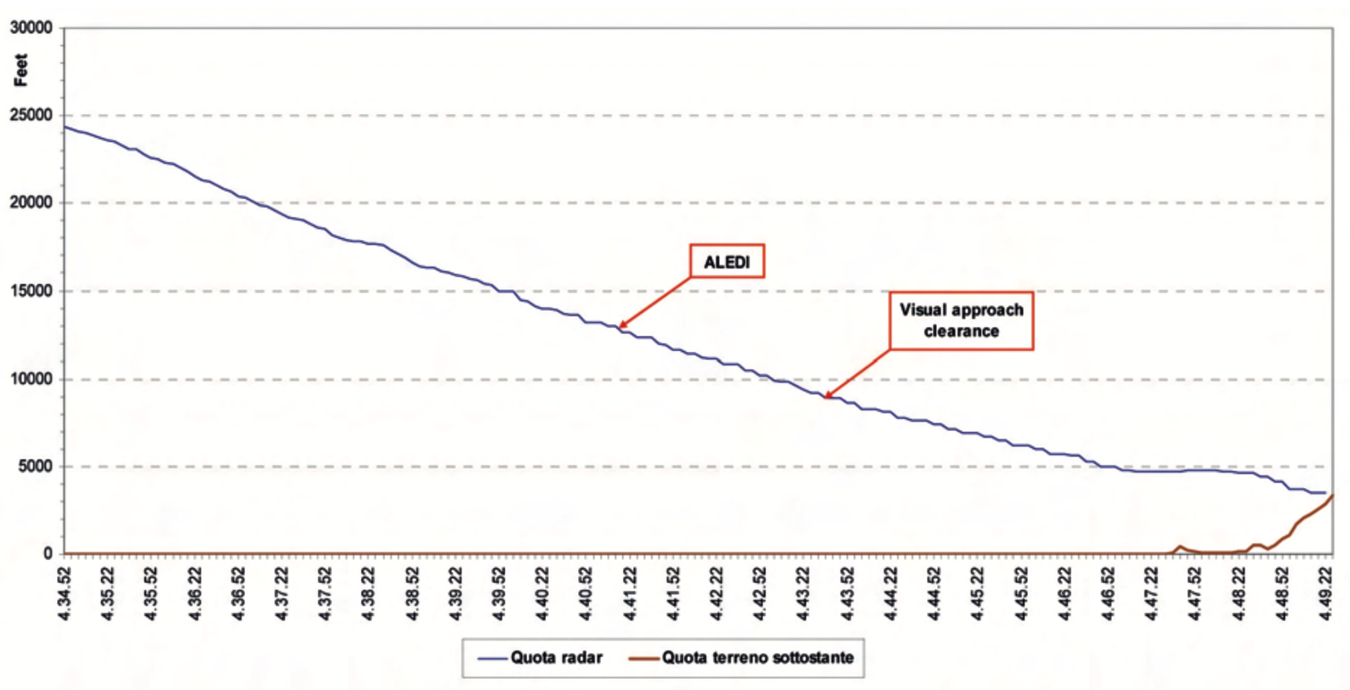


Figure 4.4: OE-FAN descent profile

4.1.2 WAI Model

The following textual description refers to the final reduced WAI model represented in Figure 4.5.

The model is composed of 12 functions (2 Background and 10 Foreground) describing the approach sequence followed during the event considered. They are divided into 2 macrocategories: CREW (green, code C.XX), ATC (blue, code ATC.XX). Acronyms and symbols are explained in the *Acronyms* section.

The model starts with the approach clearance given by the APP controller, after having outlined an arrival sequence **(ATC.1. Give ILS approach clearance)**. The flight crew then prepares for the approach, making a pre-arrival briefing **(C.1 Make approach briefing)**, where important features of the procedure are discussed, and sets the A/C accordingly **(C.3. Prepare the A/C for landing)**.

If considered feasible during the briefing, pilots can ask for a visual approach **(C.2. Ask for visual approach)**. The APP controller will then ask the crew whether they have the field in sight and if able to maintain visual separation from ground obstacles **(ATC.2. Ask to report runway and terrain in sight)**. Consequently, the crew will look outside the windshield observing the surrounding terrain and will report when these have been spotted **(C.4. Establish visual contact with the runway)**. Only after such confirmation the APP controller can authorize the change of approach type and clear the A/C for a visual approach **(ATC.3. Give clearance for visual approach)**.

Next, the Pilot Flying (PF) takes over the control of the A/C and manually flies it **(C.6. Manually fly the A/C)** to a safe touchdown and a complete stop **(C.7. Land safely)**. During this phase, the crew monitors the descent, checking the A/C distance and altitude with respect to the runway, while constantly maintaining visual contact with the obstacles present along the path and correcting the trajectory accordingly **(C.5. Monitor approach path)**.

Finally, the APP controller initiates the handoff procedure when appropriate, passing the responsibility over the A/C to the TWR controller **(ATC.4. Hand over the A/C to TWR)**, who will eventually clear the A/C to land **(ATC.5. Give landing clearance)**. The crew monitors the communications in order to spot important aspects affecting the safety and operativity of their flight.

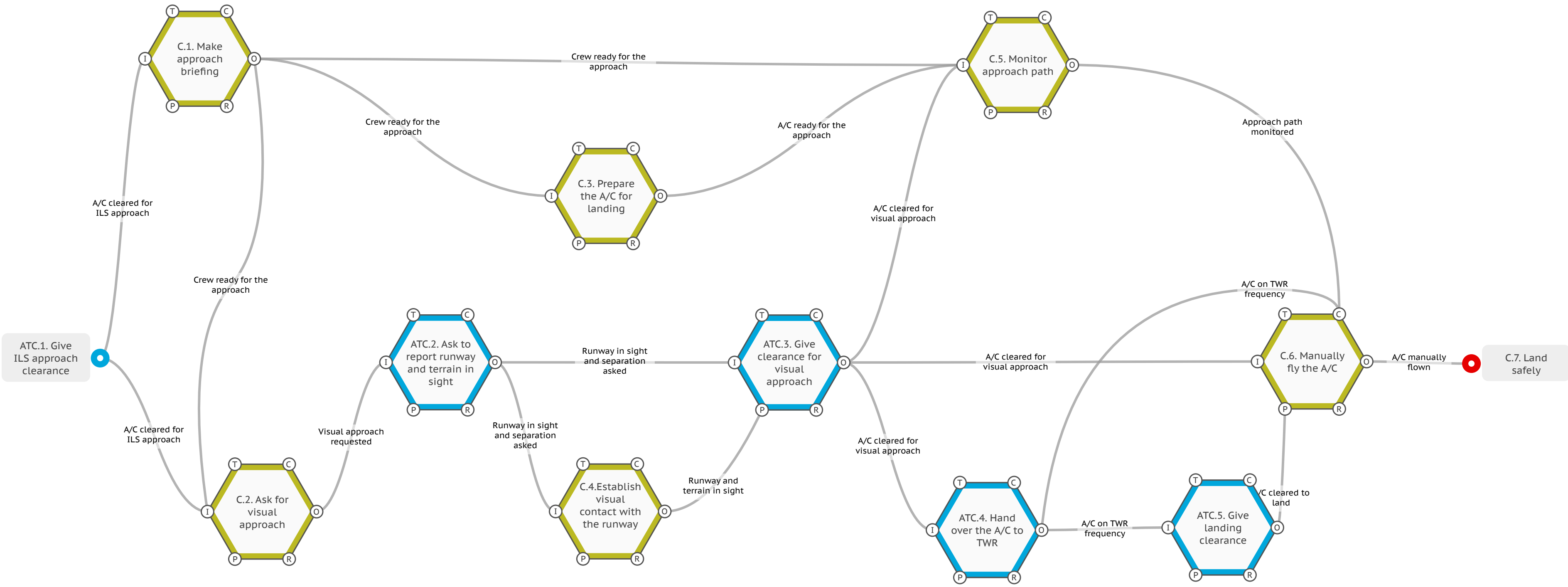


Figure 4.5: WAI model of the Cagliari accident (OE-FAN)

4.1.3 WAD Model

During the approach phase, after having already been cleared to switch to a visual approach to runway 32, the flight crew of CIT124 was exposed to the *'Black Hole'* effect, which led them to establish an erraneous visual contct with the runway. Due to the specific weather and time conditions, as well as being unfamiliar with the area, the pilots mistook the surface lights along the east coast of Sardinia with the ones of the aerodrome, therefore getting misled during the manouver.

This introduced significant variability in the system, hindering the safety of the approach **(C.4. Establish viausl contact with the runway)**.

This variability propagated downstream through **(ATC.3. Give clearance for visual approach)** to **(C.6. Manually fly the A/C)**, affecting the way the A/C was flown and eventually leading to the unfortunate CFIT outcome. This is where the accident occured.

Moreover, the approach path was not properly monitored due to incorrect readings of the terrain heights, which resulted from the colors used being easily misinterpreted. This beacame a factor as the crew initiated an early turn towards the (believed) runway, facing the mountaneous terrain east of the aerodrome.
This added up to the fact that the crew was unfamiliar with the area and there were no clear outside features to rely on, being dark at night and being the A/C over the sea. Furthermore, the crew was exposed to fatigue, having been awake for an extended period without rest at the time of the event **(C.5. Monitor approach path)**.

Finally, during the handover procedure a misunderstanding occured between Cagliari APP and the crew, who believed they were cleared to descend up to 2500 ft free of obstacles (lower than the mountaneous terrain nearby), despite having aknowledged the ability to maintain separation on their own **(ATC.4. Hand over the A/C to TWR)**.

Both functions increased the variability of the system which ultimately propagated to the manual flight function, contributing to the occurence of the accident.

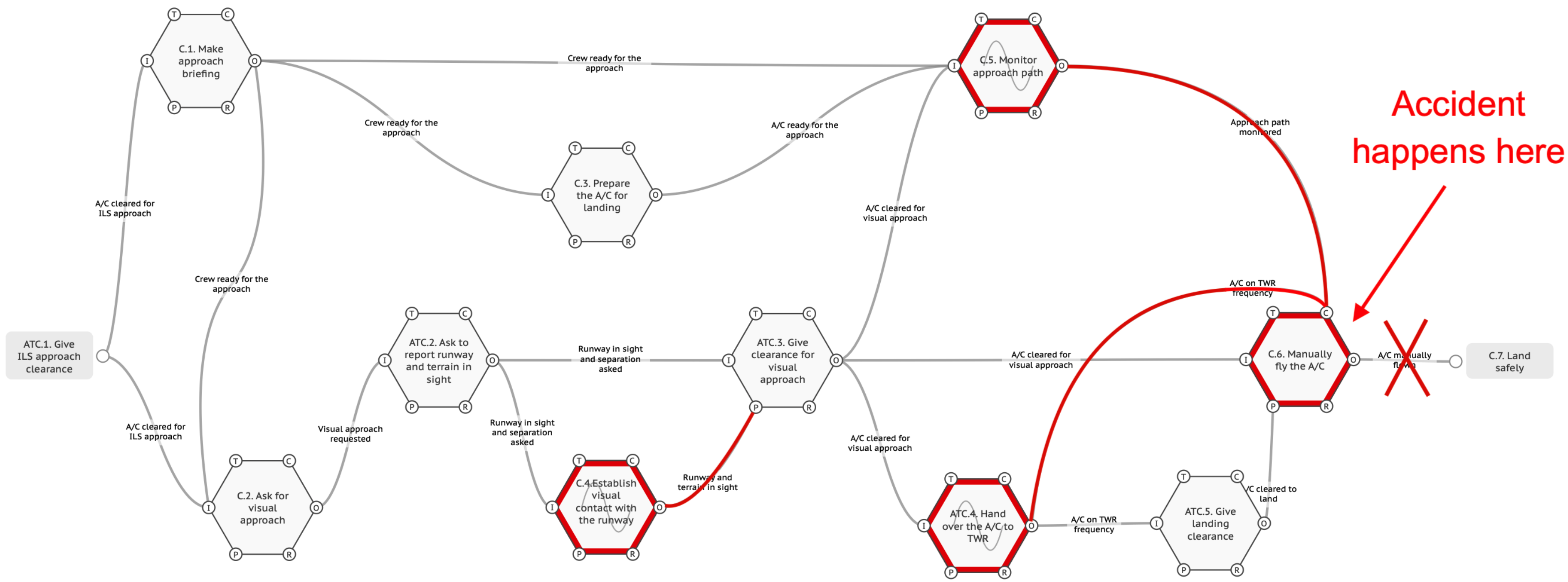


Figure 4.6: WAD model of the Cagliari accident (OE-FAN)

4.1.4 Type identification

Table 8 shows the assigned type for each function. All the acronyms and symbols used are explained in the *Acronyms* section.

ID	Name	Type
ATC1	Give ILS approach clearance	Human
ATC2	Ask to report runway and terrain in sight	Human
ATC3	Give clearance for visual approach	Human
ATC4	Hand over the A/C to TWR	Human
ATC5	Give landing clearance	Human
C1	Make approach briefing	Human
C2	Ask for visual approach	Human
C3	Prepare the A/C for landing	Human
C4	Establish visual contact with the runway	Human
C5	Monitor approach path	Human
C6	Manually fly the A/C	Human
C7	Land safely	Human

Table 8: Functions type classification with respect to variability (OE-FAN)

All the functions belong to the Human type, as they refer to a manual flight scenario where no flight instruments functions were deemed essential during the function indentification process. All these functions are performed by humans in small groups, namely the crew or the ATC controllers, therefore no Organizational type was assigned.

4.1.5 External variability

Table 9 shows the assessment of the external variability and the assigned CPC only for those funtions whose rating has been marked *Inadequate*.

ID	Name	Type	Common Performance Condition	Rating	Likely performance variability
C4	Establish visual contact with the runway	H	Number of goals and conflict resolution	Unpredictable	High
C5	Monitor approach path	H	Conditions of work	Inadequate	Noticeable
			Circadian rhythm and stress	Inadequate	Noticeable
			Availability of procedures and plans	Inadequate	Noticeable
			Team collaboration quality	Inadequate	Noticeable
ATC4	Hand over the A/C to TWR	H	Quality of communication	Inadequate	Noticeable

Table 9: External variability and CPC (OE-FAN)

Function C.4 has been assigned the CPC *"Number of goals and conflict resolution"*, which refers to the fact that the crew was exposed to the Black Hole effect. Being a visual illusion, this has been rated *Unpredictable*, which implies a *High* likely performance variability.

Function C.5 was affected by multiple CPCs. These contemplate the nightime nature of the flight, which took place after a long active duty time: *"Conditions of work"* and *"Circadian rhythm and stress"* have been therefore assigned as CPCs. Moreover, the non-familiarity with the area, the sub-optimal charts on board and the early deviation from the instrumental approach path were influenced respectively by the CPCs *"Availability of procedures and plans"* and *"Team collaboration quality"*.

Finally, function ATC.4 has been assigned the CPC *"Quality of communication"* due to the misinterpretation of the instructions given by Cagliari APP.

4.1.6 Internal variability

Table 10 describes the assessment of the internal variability. All functions are shown regardless of the rating attributed.

ID	Name	Output	Time	Precision
ATC1	Give ILS approach clearance	A/C cleared for ILS approach	On time	Precise
ATC2	Ask to report runway and terrain in sight	Runway in sight and separation asked	On time	Precise
ATC3	Give clearance for visual approach	A/C cleared for visual approach	On time	Precise
ATC4	Hand over the A/C to TWR	A/C on TWR frequency	On time	Imprecise
ATC5	Give landing clearance	A/C cleared to land	On time	Precise
C1	Make approach briefing	Crew ready for the approach	On time	Precise
C3	Prepare the A/C for landing	A/C ready for the approach	On time	Precise
C4	Establish visual contact with the runway	Runway and terrain in sight	On time	Imprecise
C5	Monitor approach path	Approach path monitored	On time	Imprecise
C6	Manually fly the A/C	A/C manually flown	On time	Precise
C7	Land safely	-	On time	Precise

Table 10: Internal variability (OE-FAN)

Function ATC.4 was rated *Imprecise* due to the miscommunication which took place during the handoff procedure between Cagliari APP and the crew.

Functions C.5 and C.5 have also been rated *Imprecise*.

The former was affected by the Black Hole effect which made the crew erraneously perceive their spatial orientation with respect to the (believed) runway, while the latter was not carried out correctly.

4.1.7 Aggregated variability

Table 11 represents the assessment of the aggreagated variability, considering only the couplings which contributed to its propagation.

Upstream function	Output	Variability		Downstream function	Effect	Variability propagation scale	
						+/-	3 levels
C.4. Establish visual contact with the runway	Runway and terrain in sight	On time Imprecise	P	ATC.3. Give clearance for visual approach	Loss of accuracy Imprecise start of the function	V+	High 3+
C.5. Monitor approach path	Approach path monitored	On time Imprecise	C	C.6. Manually fly the A/C	Loss of accuracy Imprecise control of the function	V+	Medium 2+
ATC.4. Hand over the A/C to TWR	A/C on TWR frequency	On time Precise	I	ATC.5. Give landing clearance	No effect	V=	Neutral 0
		On time Imprecise	C	C.6. Manually fly the A/C	Misunderstanding	V+	Low 1+

Table 11: Aggregated variability and couplings (OE-FAN)

In this occurence, only one function has *Highly* affected its downstream functions, heavily contributing to the propagation of variability and to the unfortunate outcome, namely function C.4.

The specific environmental conditions made the pilots believe that the lights on the east coast of Sardinia were instead the ones of the runway. This mispercpetion propagated through function ATC.4, as the controller cleared the A/C for a visual approach upon receiving confirmation of such visual contact, despite being imprecise.
This ultimately propagated to function C.7, highly affecting the way the pilots manually flown the A/C since using these erraneous references.

The control exerted by function C.5 over this function also propagated its variability, further amplifying the variability already accumulated. This propagation has been rated *Medium*.

Finally, the misunderstanding during the handoff procedure played a role in the overall system variability, despite being of a lower impact since the crew had reported able to maintain separation from obstacles on their own.

4.2 Narsarsuaq accident (D-CBNA)

The event has occurred on August, 5th 2001 at 04:43 UTC involving a Dassault Falcon 20 registration D-CBNA while in approach to Narsarsuaq, Greenland (BGBW). The aircraft was operating a non-scheduled cargo flight from Gdańsk (EPGD) to Louisville (KSDF), with intermediate refueling stops planned, including at BGBW.

Section 4.2.1 presents a brief summary of the event. Section 4.2.2 descibes the WAI model represented in Figure 4.11 while Section 4.2.3 outlines the WAD model.

All the factual information have been taken from official sources, namely the official report by the Danish Aircraft Accident Investigation Board (AAIB) and its Annexes [6].

Figure 4.7: D-CBNA at Uherské Hradište-Kunovice Airport (© Václav Kudela 2000, aviation-safety.net)

4.2.1 Description of the event

During the descent towards Narsarsuaq the A/C reported to the FIS operator passing FL195. Meanwhile, the crew made a pre-arrival briefing for the NDB/DME approach RWY 07.

When at 10 NM out of the field, the pilots were instructed to contact the AFIS operator at BGBW, who reported the latest area information regarding traffic and weather. The AFIS operator also tried to establish a visual contact with the A/C but unsuccessfully.

Shortly after, the A/C impacted the mountainous terrain situated approximately 4.5 NM out of the aerodrome, at about 700 ft MSL.
All the occupants lost their lives and the A/C was destroyed.

The investigation revealed that the flight crew made in fact a visual approach as opposed to the NDB/DME approach discussed during the briefing.

The actual path followed can be seen squared in Figure 4.9, ending with the impact point. This can be compared with the expected path drawn in dotted lines in Figure 4.9, as well as in the NDB/DME approach chart in Figure 4.8.
The human factor was a heavily contributing element in the event.

During both descent and approach phases, there have been a total lack of CRM and the crew did not adhere to SOPs (checklist, approach procedure, altitude calls).
An example of an SOP for a non-precision VOR/ADF approach can be seen in Figure 4.10.

Moreover, multiple data has proved the crew to be subject to high fatigue: both pilots showed signs of stress, as reported by the ramp agent at Gdansk, worsened by the delay matured during the previous flights. Flight records also showed that the maximum crew duty time was exceeded by almost 3 hours.

In addition, the GPWS was found to be inoperative, since no aural calls were recorded by the CVR, even though this was allowed by the operator's Minimum Equipment List (MEL).

Finally, the crew may have experienced the visual illusion phenomenon known as *'Black Hole'*, which may have led the pilots to erraneously perceive their position relative to the runway and the ground.

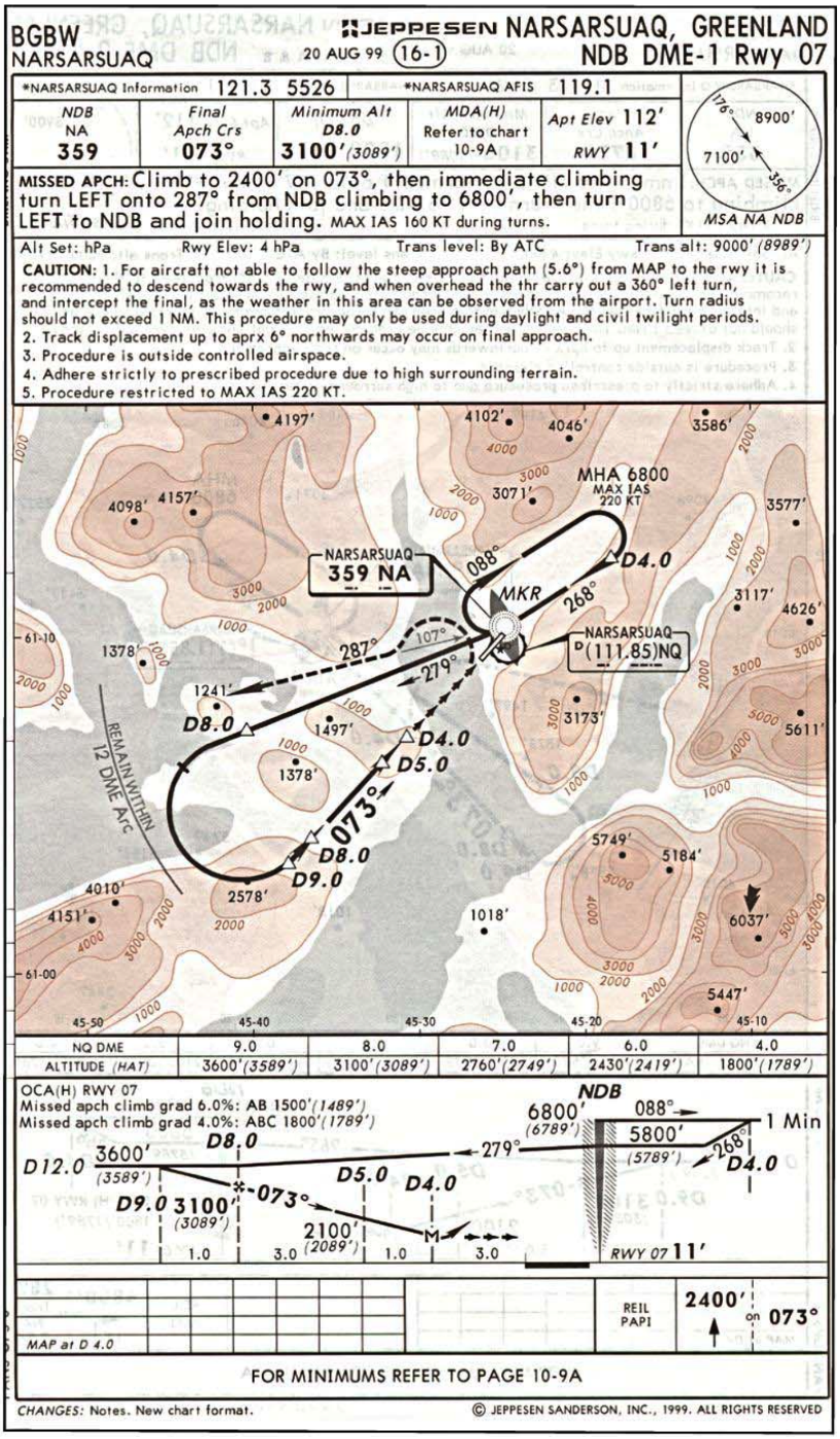


Figure 4.8: NDB/DME RWY07 Jeppesen chart

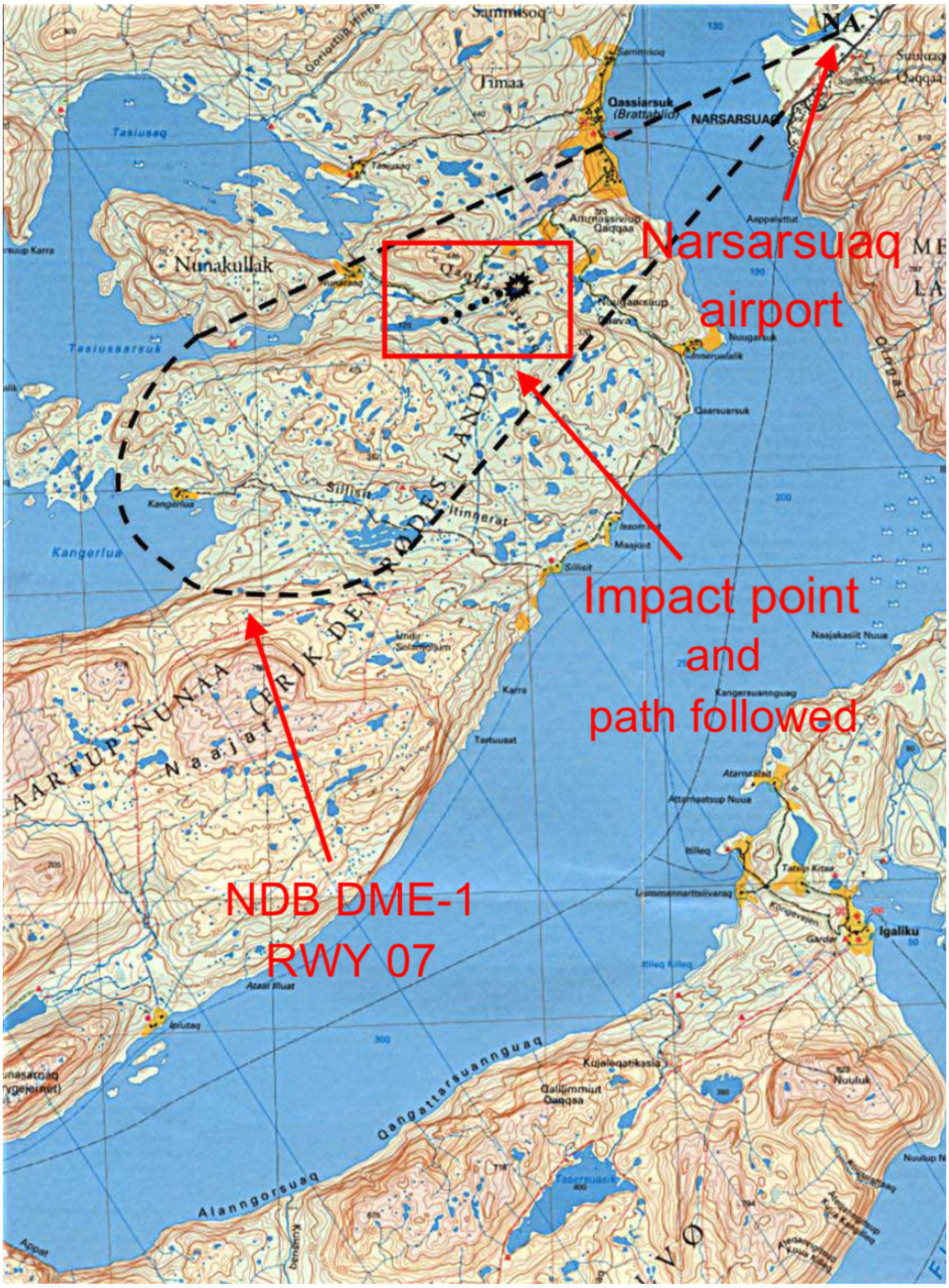


Figure 4.9: Path followed and impact point

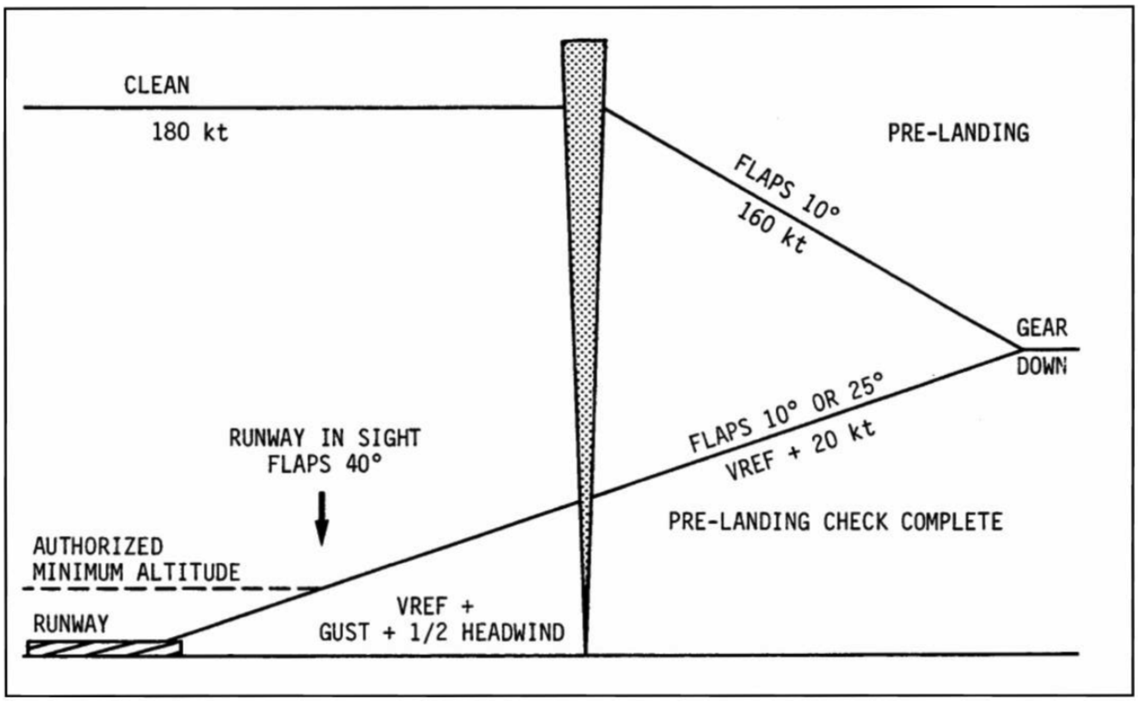


Figure 4.10: Example of an SOP for a two-engine VOR/ADF approach

4.2.2 WAI Model

The following textual description refers to the final reduced WAI model represented in Figure 4.11.

The model is composed of 13 functions (2 Background and 11 Foreground) describing the approach sequence followed during the event considered. They are divided into 3 macrocategories: CREW (green, code C.XX), ATC (blue, code ATC.XX) and ON-BOARD SYSTEMS (purple, code S.XX). Acronyms and symbols used are explained in the *Acronyms* section.

The model starts with the A/C descending outside the controller airspace **(C.1. Start the discent)**, followed by the pre-arrival briefing performed by the flight crew in order to highlight the main features of the approach procedure **(C.2. Make approach briefing)**. The A/C is then set for landing **(C.3. Prepare the A/C for landing)** and, when appropriate, the Enroute controller hands it over it to the AFIS controller **(ATC.1. Hand over the A/C to AFIS)**.

The descent is initially performed by the autopilot, so it is automatic **(S.2. Fly following the horizontal NAV signal)**. Then, when a visual contact with the runway has been established **(C.6. Establish visual contact with the runway)**, the Pilot Flying (PF) takes over the control of the A/C and manually flies it **(C.7. Manually fly the A/C)** to a safe touchdown and a complete stop **(C.8. Land safely)**.

During both the descent and the approach, pilots are expected to follow precise procedures listed in the company SOPs, including the use of checklists **(C.5. Perform SOPs and checklist)**, and to cross-monitor altitude, distance and speed, accomplished by comparing the aircraft current flight data to the external environment and the expected approach path **(C.4. Monitor approach path)**. Moreover, during both phases, the avionic system monitors integrity of the signals received as well as crucial parameters such as the sink rate, the distance from terrain, etc. contributing to increase crew's full situational awareness **(S.1. Monitor signals and terrain)**.

Once the crew has reported on final, the AFIS operator tries to establish a visual contact with the A/C **(ATC.2. Establish visual contact with the A/C)**, keeping it until landing in order to provide the best area information regarding traffic and weather as well as the most updated runway conditions **(ATC.3. Report tfc, rwy and weather status)**. Given the nature of the AFIS, these are not constrains and the flight crew will autonomously decide whether to continue with the approach and landing or not.

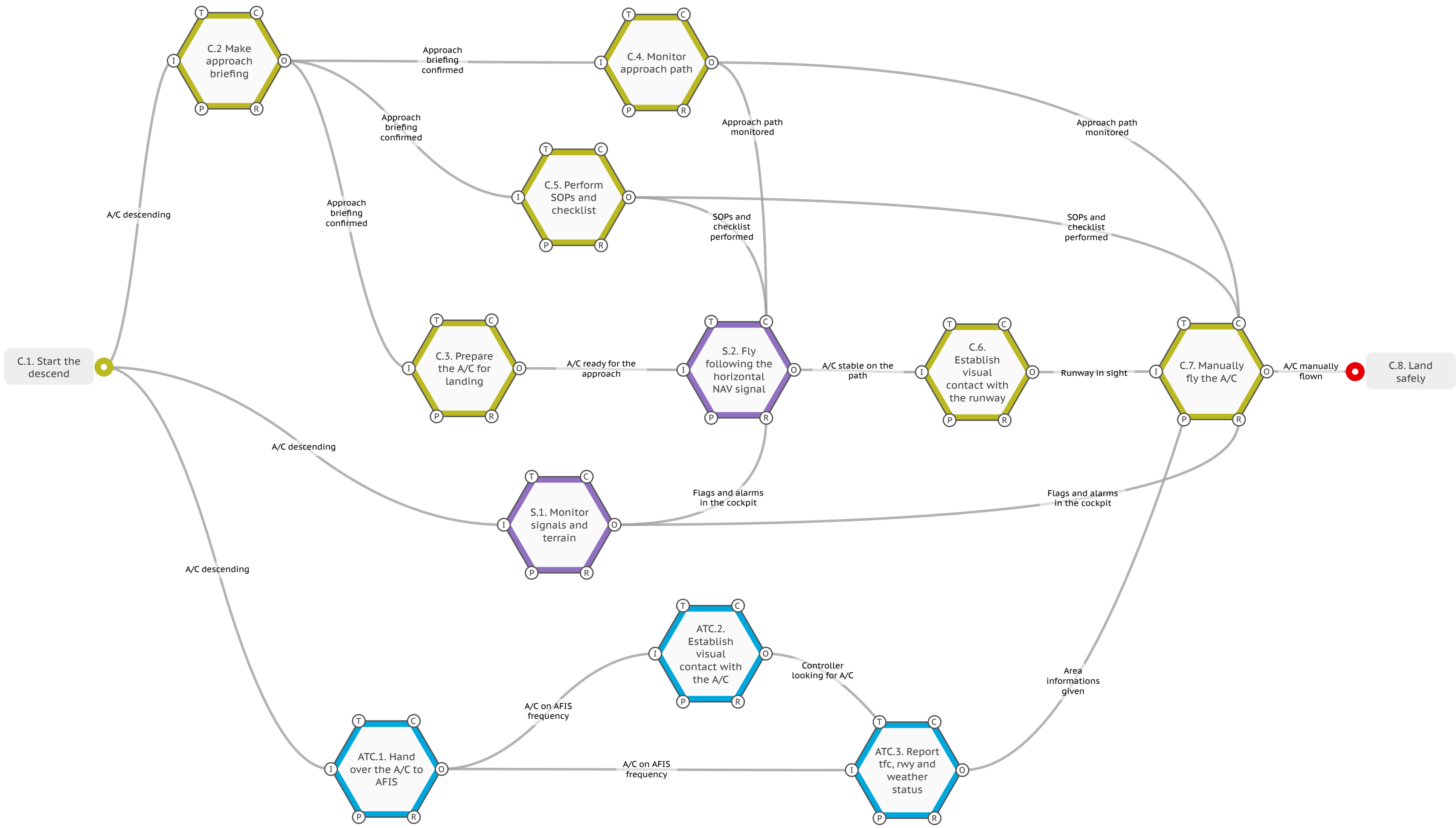


Figure 4.11: WAI model of the Greenland accident (D-CBNA)

4.2.3 WAD Model

During the descent the variability of the system was increased by the non-adeherence to the company SOPs, as the crew did not follow the pre-briefed non-precision NDB/DME approach but instead switched to a visual approach meanwhile not complying with the required procedures **(C.5. Perofrm SOPs and checklist)**.

Ath the same time, the approach path was not correctly monitored as no altitude calls were made. The nightime nature of the flight and the symptoms of fatigue resulting from the prolonged duty time, exceeded by almost 3 hours, further affected this function **(C.4. Monitor approach path)**.
Moreover, the GPWS on-board was inoperative (allowed by the operator's MEL) which further increased the overall variability of the system since no terrain warnings could be issued **(S.1. Monitor signals and terrain)**.

Couplings of these functions with the manual flight function **(C.7. Manually fly the A/C)** were therefore interrupted, removing their control and resource action over it. This left function C.7 prone to resonance; indeed, the accident eventually occurred here.

Function **(C.6. Establish visual contact with the runway)** was what actually made the manual flight function to resonate: the crew was exposed to the *Black Hole* effect which led them to mistakenly assume their position relative to the ground, hence making them fly on a wrong path and rate of descent untill the impact with the ground.

The variabiliy introduced by functions C.4, C.5 and S.1 initially propagated to function **(S.2. Fly following the horizontal NAV signals)**, which in turn propagated to function C.6 since, when deciding to switch to a visual approach and took over the control of the A/C, the flight crew was subject to its effects. Function C.6 was the one that ultimately pushed the system's variabilty over its resilience threshold, which happened in function C.7. This last function was already heavily impacted by the excessive variability introduced by functions C.4, C.5 and S.1, such that function C.6 only became the primer.

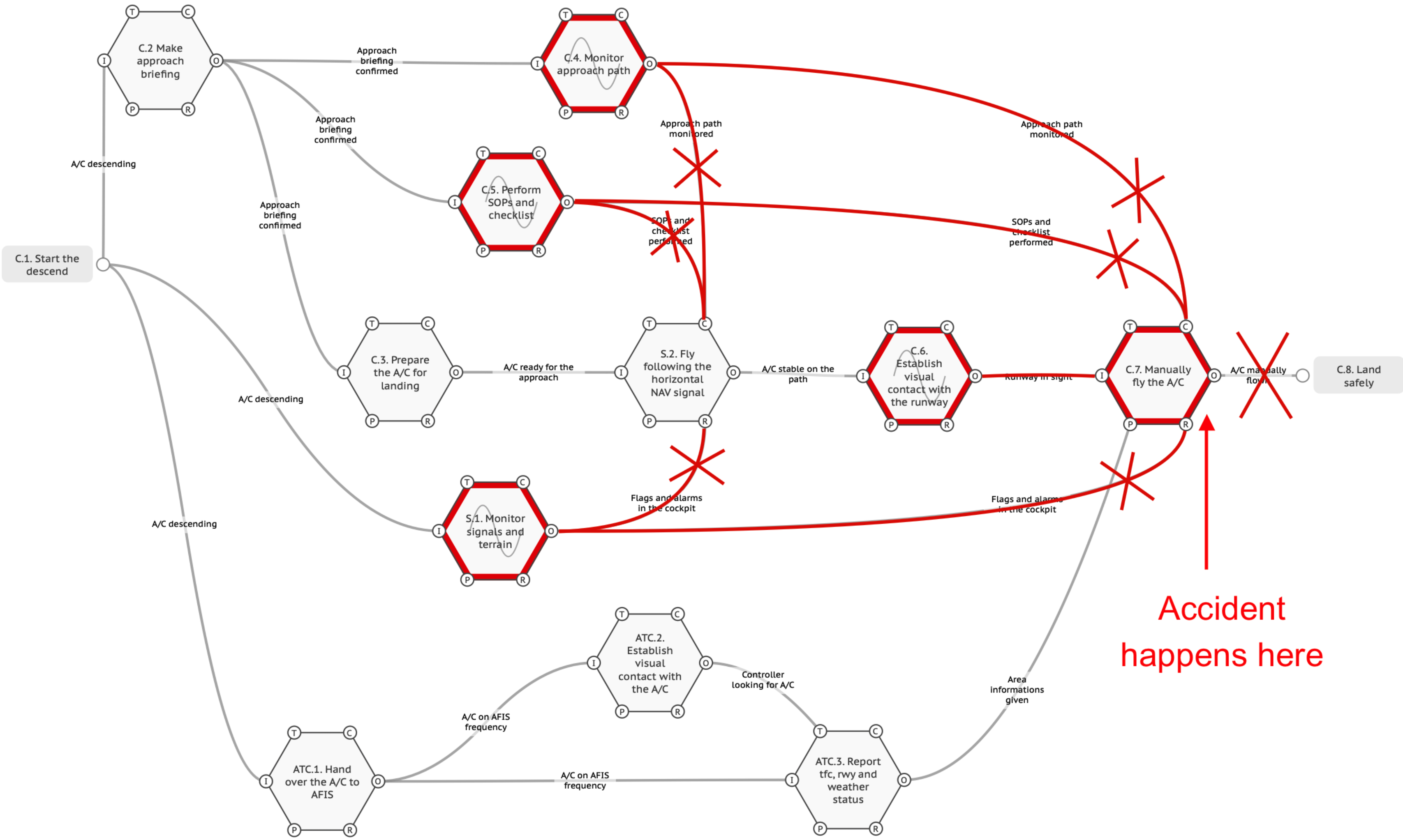


Figure 4.12: WAD model of the Greenland accident (D-CBNA)

4.2.4 Type identification

Table 12 shows the assigned type for each function. All the acronyms and symbols used are explained in the *Acronyms* section.

ID	Name	Type
ATC1	Hand over the A/C to AFIS	Human
ATC2	Establish visual contact with the A/C	Human
ATC3	Report tfc, rwy and weather status	Human
C1	Start the descend	Human
C2	Make approach briefing	Human
C3	Prepare the A/C for landing	Human
C4	Monitor approach path	Human
C5	Perform SOPs and checklist	Human
C6	Establish visual contact with the runway	Human
C7	Manually fly the A/C	Human
C8	Land safely	Human
S1	Monitor signals and terrain	Technological
S2	Fly following the horizontal NAV signal	Technological

Table 12: Functions type classification with respect to variability (D-CBNA)

It can be seen that the majority of the functions belong to the Human type. These are performed by humans in small groups, namely the crew or the ATC controllers, therefore no Organizational type was assigned.

Functions S.1 and S.2 are of type Technolgical since they refer to the functions performed by on-board systems such as the avionics and the GPWS.

4.2.5 External variability

Table 13 shows the assessment of the external variability and the assigned CPC only for those funtions whose rating has been marked *Inadequate*.

ID	Name	Type	Common Performance Condition	Rating	Likely performance variability
C4	Monitor approach path	H	Conditions of work	Inadequate	Noticeable
			Circadian rhythm and stress	Inadequate	Noticeable
			Team collaboration quality	Inadequate	Noticeable
C5	Perform SOPs and checklist	H	Circadian rhythm and stress	Inadequate	Noticeable
			Availability of procedures and plans	Inadequate	Noticeable
			Team collaboration quality	Inadequate	Noticeable
C6	Establish visual contact with the runway	H	Number of goals and conflict resolution	Unpredictable	High

Table 13: External variability and CPC (D-CBNA)

Functions C.4 and C.5 were affected by multiple CPCs. These contemplate the long active duty time, which eventually led to an excess of almost 3 hours. *"Conditions of work"* and *"Circadian rhythm and stress"* have been therefore assigned as CPCs. Moreover, the nightime nature of the flight as well as the non-adeherence to the SOPs were influenced respectively by the CPCs *"Availability of procedures and plans"* and *"Team collaboration quality"*.

Function C.6 has been assigned the CPC *"Number of goals and conflict resolution"*, which refers to the fact that the crew was exposed to the Black Hole effect. Being a visual illusion, this has been rated *Unpredictable*, which implies a *High* likely performance variability.

4.2.6 Internal variability

Table 14 describes the assessment of the internal variability. All functions are shown regardless of the rating attributed.

ID	Name	Output	Time	Precision
ATC1	Hand over the A/C to AFIS	A/C on AFIS frequency	On time	Precise
ATC3	Report tfc, rwy and weather status	Area information given	On time	Precise
C1	Start the descend	A/C descending	On time	Precise
C2	Make approach briefing	Approach briefing confirmed	On time	Precise
C3	Prepare the A/C for landing	A/C ready for the approach	On time	Precise
C4	Monitor approach path	Approach path monitored	Not at all	-
C5	Perform SOPs and checklist	SOPs and checklist performed	Not at all	-
C6	Establish visual contact with the runway	Runway in sight	On time	Imprecise
C7	Manually fly the A/C	A/C manually flown	On time	Precise
C8	Land safely	-	On time	Precise
S1	Monitor signals and terrain	Flags and alarms in the cockpit	Not at all	-
S2	Fly following the horizontal NAV signal	A/C stable on the path	On time	Precise

Table 14: Internal variability (D-CBNA)

In the instantiation considered, functions C.4 and C.5 were not carried out and have therefore been rated *Not at all*.

Function C.6 has been rated *Imprecise*. Indeed, such task was carried out imprecisely due to the Black Hole effect visual illusion, which made the crew perceive an erraneous spatial orientation of the A/C with respect to the runway.

Finally, function S.1 has been rated *Not at all* since the GPWS was inoperative, therefore not able to perform its designed tasks, despite being allowed by the operator's MEL.

4.2.7 Aggregated variability

Table 15 represents the assessment of the aggreagated variability, considering only the couplings which contributed to its propagation.

Upstream function	Output	Variability	Downstream function		Effect	Variability propagation scale	
						+/-	3 levels
C.4. Monitor approach path	Approach path monitored	Not at all	C	S.2. Fly following the horizontal NAV signal	Control input may be missed	V+	High 3+
			C	C.7. Manually fly the A/C	Control input may be missed	V+	High 3+
C.5. Perform SOPs and checklist	SOPs and checklist performed	Not at all	C	S.2. Fly following the horizontal NAV signal	Control input may be missed	V+	High 3+
			C	C.7. Manually fly the A/C	Control input may be missed	V+	High 3+
C.6. Establish visual contact with the runway	Runway in sight	On time Imprecise	I	C.7. Manually fly the A/C	Loss of accuracy Imprecise start of the function	V+	High 3+
S.1. Monitor signals and terrain	Flags and alarms in the cockpit	Not at all	R	S.2. Fly following the horizontal NAV signal	Resource input may be missed	V+	Medium 2+
			R	C.7. Manually fly the A/C	Resource input may be missed	V+	Medium 2+

Table 15: Aggregated variability and couplings (D-CBNA)

In this occurence, multiple functions have *Highly* affected their downstream functions, heavily contributing to the propagation of variability, namely function C.4, C.5 and C.6.

The lack of SOPs during the whole duration of the approach, as well as the lack of monitoring of the surrounding terrain and expected altitudes, introduced and propagated a high ammount of variability to both the automatic and manual flight functions (S.2 and C.7). Both functions removed important safety control barriers, which initially affected function S.2 and, subsequently, led the system's variability to increase and build up in C.7.

The variability introduced by function C.6 propagated to C.7. This function was influenced by the Black Hole effect and was the one that made the overall performance variability (already piled up here) to diverge and exceed the system threshold, leading to the unfortunate outcome.

Likewise, variability of function S.1 had a meaningful impact on both functions S.2 and C.7 but has been rated *Medium* since this was allowed by the MEL.

5 Comparison and Commonalities

This Chapter presents the aggregated analysis conducted following the FRAM study of each occurrence, comparing the results obtained in order to identify possible commonalities within the functions involved as well as the associated Human Factors and Mitigations.

This approach enables to gain tangible insights of the occurrences by assessing the Human Factors which affected their elementary functions. By means of comparison and identification of shared features, it was possible to determine those elements which affected the system in the different study cases and to draw the appropriate conclusions.

Unfortunately, the traditional FRAM method falls short of providing a direct way to identify such Human Factors. However, this is a crucial aspect, vital in the aviation industry, since no flight safety improvements can be achieved without practical considerations and concrete mitigation actions.

Because of this, within the DIMEAS department of Politecnico di Torino, multiple works have been carried on to study a way of providing a link between the FRAM analysis and Human Factors. The method developed is originally based on the HFACS taxonomy, widely accepted as a universal source for safety recommendations in the aviation industry. Multiple way of linking have been tested. [8] [11] [21]

In this project, a mapping based on the CPCs attributed to the varying functions has been implemented. This mapping links the CPCs to the ICAO SHELL Human Factors, which in turn are linked to the HFACS taxonomy, providing therefore an intermediate link between FRAM and HFACS. Figure 5.1 shows the complete linking process.

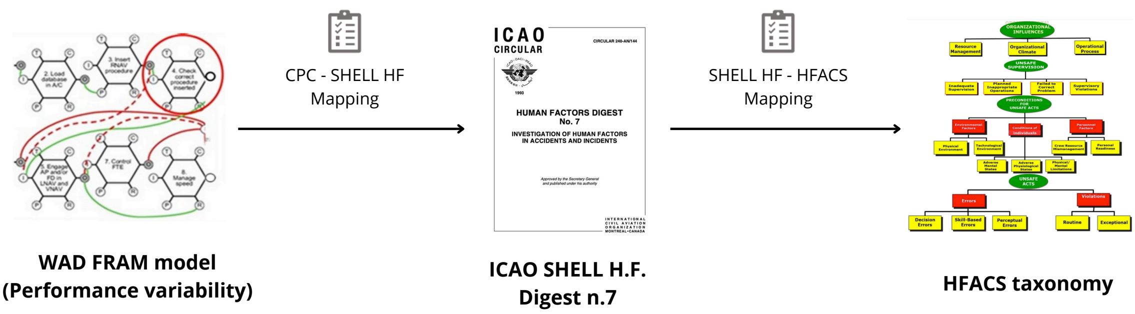


Figure 5.1: FRAM - SHELL HF - HFACS mapping process

The steps described in this Chapter correspond to Phase 3 and 4 of the implemented analysis method.

Section 5.1 outlines the common functions identified, with their respective variability propagation level (Phase 3). Section 5.2 describes the Human Factors determined for each event and a comprehensive comparison among them, while Section 5.3 briefly suggests possible mitigation actions based on the HFACS nanocodes classification (Phase 4).

5.1 Common functions identification

Functions			Oslo occurrence (LN-KKL)	Cagliari occurrence (OE-FAN)	Greenland occurrence (DCBNA)	Average	
N.	**Name**	**Type**				**Decimal**	**Level**
1	Hand over the A/C to TWR	H	Medium 2+	Low 1+	Neutral 0	1	Low 1+
2	Make approach briefing	H	Neutral 0	Neutral 0	Neutral 0	0	Neutral 0
3	Prepare the A/C for landing	H	Neutral 0	Neutral 0	Neutral 0	0	Neutral 0
4	Monitor approach path	H	High 3+	Medium 2+	High 3+	2.667	High 3+
5	Establish visual contact with the runway	H	High damp 3-	High 3+	High 3+	1	Low 1+
6	Manually fly the A/C	H	Neutral 0	Neutral 0	Neutral 0	0	Neutral 0
7	Land safely	H	N/A	N/A	N/A	N/A	N/A
8	Capture and fly following ILS signals	T	Medium 2+	N/A	Neutral 0	1	Low 1+
9	Monitor signals and terrain	T	High 3+	N/A	Medium 2+	2.5	High 3+

Table 16: Common functions identified and relative variability propagation level

Table 16 shows the *nine* common functions identified, found to be present in at least 2 (out of 3) occurrences analyzed. As it can be seen, the majority of them are of type Human, mainly referring to tasks performed by the flight crew, with only one associated to ATC duties. The remaining two are of type *Technological* and refer to tasks performed by the avionics and the monitoring on-board systems.

For every function, the associated variability propagation level specific to each event has been reported, as well as the resulting average index. The decimal value initially calculated has been subsequently rounded up to find the final mean level. *(Note that when the function was not present or was not a foreground function, a value N/A has been assigned.)*

Functions **Monitor approach path** and **Monitor signals and terrain** revealed to be the ones contributing the most to the propagation of variability, ranking **High** on average. It is interesting to note that both functions involve monitoring and, therefore, take on a supervisory role over another function, in these cases the act of flying the aircraft.

Function **Establish visual contact with the runway** was rated **Low** on average, but it is worth analyzing where this index stems from. Both *dampening* and *amplifying* values have been assigned among the different occurrences, therefore denoting that such function can actually *highly* contribute to variability.

Indeed, in the Oslo event this function was the one that dampened the variability accumulated and eventually prevented the accident, while in the other two this was the kickstarter which made the system's variability diverge from the already high ammount built up.

Finally, functions **Hand over the A/C to TWR** and **Capture and fly following ILS signals** were rated **Low** on average while the last three functions were averagely rated **Neutral**. **Land the A/C** was a background function in all the events, thus it was never assigned a variability level.

5.2 Human Factors

After having identified the common functions and having validated the analysis conducted, *Phase 4 (Comparative analysis & Mitigations)* has been performed.

The first step consisted in identifying the Human Factors affecting the *human* functions having *at least one CPC* rated 'Inadequate' or 'Unpredictable' for each occurrence. This task corresponds to the first part of the mapping process discussed at the beginning of Section 5, as shown in Figure 5.2.

This has been done with the help of the first mapping table produced, linking the CPCs to the SHELL Human Factors. The mapping was build by associating to each CPC all the possible Human Factors which could be referred to its description.
ICAO Human Factors Digest n.7 and, in particular, Checklist B present in Annex 1, was used as a reference in this process. [20]

CPCs represent those environmental and socio-technical factors which might affect the external variability of a function in a particular instantiation of the system, inducing it to differ from the potential variability addressed in the *Work-As-Imagined* model.
Based on the specific conditions described by each CPC, both *'Individual'* and *'Interactions'* related SHELL Human Factors have been attributed, also making use of the guidelines present in *Appendix 3 - Explanatory Human Factors* of the Digest.

This first intermediate link has been chosen as it provides the most direct and easiest way of introducing the Human Factors in the FRAM methodology, being composed of fewer entries than the HFACS taxonomy, further reducing the possibility of errors or misinterpretations by the investigator in the process.

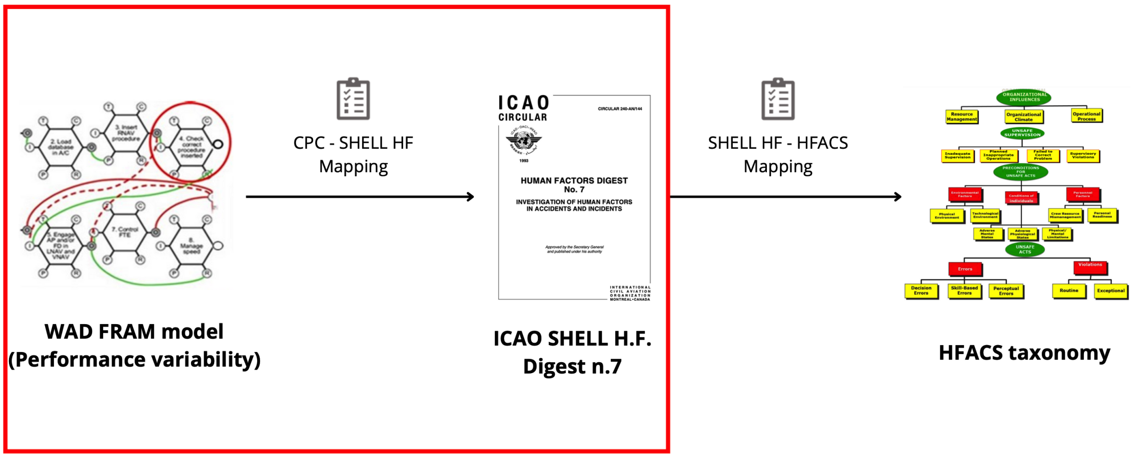


Figure 5.2: Focus of Section 5.2 - first mapping process

- **Oslo occurrence (LN-KKL)**

  Table 17 shows the HF associated to the human common functions of LN-KKL.

  Function **Hand over the A/C to TWR** was assigned, through the CPC *Quality of Communication*, three HF which refer to the poor handoff sequence, in particular the lack of readback by the crew and the assumptions made by the APP. Also, the malfunction in the controller's headset represents a Liveware/Hardware factor.

  The same factors apply equally to function **Confirm A/C is on frequency** and **Switch to TWR frequency**. In this last case, the high-workload situation may have also played a role in delaying the frequency switch, since it induced pilots to a channelized attention towards the multiple issues happening (*Distraction/Channelized attention* and *Task saturation*).

  The same Human Factor also affected function **Monitor approach path**. Also, the combination of the nighttime and adverse weather conditions (*Liveware/Environment - Other factors and Weather*), confusion generated by the inadequate EADI GS indicator (*Liveware/Hardware - Equipment*) and disorientation caused by the erroneous perception of the A/C distance from the runway (*Psychological - Perception*), contributed to its improper execution.

  Moreover, it is to note that both pilots were experienced with a high number of flight hours, which may have led to an *Overconfidence* and *Complacency* attitude.

  Finally, the dampening action exerted by function **Establish visual contact with the runway** was influenced by the knowledge of procedures (*Psychological - Procedures*), which prevents landing without a positive visual contact with the runway, and the decision-making process performed during the judgement of the approach conditions (*Psychological - Information processing*).

  In this regard, training was foundamental for the development and right implementation of such skills.

ID	Name	Common Performance Condition	SHELL Human Factors
ATC3	Hand over the A/C to TWR	Quality of communication	Individual - Psychological - Attitude/moods *(Expectations-False hypothesis)*
			Interactions - Liveware/Liveware - Oral communication *(Readback,Hearback)*
			Interactions - Liveware/Hardware - Equipment
ATC4	Confirm A/C is on TWR frequency	Quality of communication	Interactions - Liveware/Liveware - Supervision (*Operational supervision)*
		Team collaboration quality	Interactions - Liveware/Liveware - Controllers *(Coordination)*
C4	Monitor approach path	Adequacy of HMI and operational support	Interactions - Liveware/Hardware - Equipment *(Switches, controls, displays)*
		Conditions of work	Interactions - Liveware/Environment - Weather
			Interactions - Liveware/Environment - Other factors
		Number of goals and conflict resolution	Individual - Psychological - Perceptions *(Disorientation)*
		Available time and time pressure	Individual - Psychological - Attention *(Distraction / Channelized attention)*
			Individual - Psychological - Workload *(Task saturation)*
		Team collaboration quality	Individual - Psychological - Attitudes/moods *(Overconfidence)*
			Individual - Psychological - Attitudes/moods *(Complacency)*
C5	Switch to TWR frequency	Quality of communication	Interactions - Liveware/Liveware - Oral communication *(Phraseology)*
		Available time and time pressure	Individual - Psychological - Attention *Distraction / Channelized attention)*
			Individual - Psychological - Workload *(Task saturation)*
C6	Establish visual contact with the runway	Training and experience	Individual - Psychological - Information processing *(Decision making / Judgement)*
			Individual - Psychological - Knowledge (*Procedures*)

Table 17: SHELL Human Factors attributed to the Oslo occurrence

- **Cagliari occurrence (OE-FAN)**

Table 18 shows the HF associated to the human common functions of OE-FAN:

ID	Name	Common Performance Condition	SHELL Human Factors
C4	Establish visual contact with the runway	Number of goals and conflict resolution	Individual - Physiological - Illusions - Visual *(Black Hole)*
C5	Monitor approach path	Conditions of work	Interactions - Liveware/Environment - Other factors
		Circadian rhythm and stress	Individual - Physiological - Fatigue *(Duty / Sleep)*
		Availability of procedures and plans	Individual - Psychological - Experience/recency *(on route, aerodrome)*
			Interactions - Liveware/Software - Written information *(Maps and charts)*
		Team collaboration quality	Individual - Psychological - Attitudes/moods *(Overconfidence)*
			Individual - Psychological - Attitudes/moods *(Complacency)*
ATC4	Hand over the A/C to TWR	Quality of communication	Interactions - Liveware/Liveware - Oral communication *(Misinterpretation)*

Table 18: SHELL Human Factors attributed to the Cagliari occurrence

The specific nature of the flight, namely the nighttime and the prolonged pilots' duty time, have been factors affecting function **Monitor approach path** (*Liveware/Environment - Other factors* and *Physiological - Fatigue*).

Other contributing factors stem from the fact that the crew was not familiar with the area and the on-board charts were found to be misleading (*Liveware/Software - Written information* and *Physiological - Experience/Recency*), as well as the possible *Overconfidence* and *Complacency* attitude which might have led to the anticipation of the approach path deviation.

The same conditions possibly contributed to the onset of the Black Hole effect *(Psychological - Illusion factor)*, which heavily affected function **Establish visual contact with the runway** and led to the erroneous perception of the A/C position and distance from the terrain.

Finally, an *Oral communication* factor played a role in function **Hand over the A/C to TWR**, since there was a misinterpretation in the instructions given by the APP controller.

- **Greenland occurrence (D-CBNA)**

  Table 19 shows the HF associated to the human common functions of D-CBNA:

ID	Name	Common Performance Condition	SHELL Human Factors
C4	Monitor approach path	Conditions of work	Interactions - Liveware/Environment - Other factors
		Circadian rhythm and stress	Individual - Physiological - Fatigue *(Duty / Sleep)*
		Team collaboration quality	Individual - Psychological - Attitudes/moods *(Overconfidence / Complacency)*
C5	Perform SOPs and checklist	Circadian rhythm and stress	Individual - Physiological - Fatigue *(Duty / Sleep)*
		Availability of procedures and plans	Interactions - Liveware/Software - Written information *(Standard Operating Procedures)*
			Individual - Psychological - Knowledge *(Procedures)*
		Team collaboration quality	Individual - Psychological - Attitudes/moods *(Overconfidence)*
			Individual - Psychological - Attitudes/moods *(Complacency)*
C6	Establish visual contact with the runway	Number of goals and conflict resolution	Individual - Physiological - Illusions - Visual *(Black Hole)*

Table 19: SHELL Human Factors attributed to the Greenland occurrence

Function **Monitor approach path** was influenced by multiple human factors: the nighttime nature of the flight (*Liveware/Environment - Other factors*), the exceeded duty time with its resulting fatigue (*Physiological - Fatigue*) and the possible *Overconfidence* and *Complacency*, which may have led the monitoring task to fail.

These last two factors, contributed also to make function **Perform SOPs and checklist** to vary, leading to the lack of procedures followed during this phase. Factors *Liveware/Software - Written information* and *Psychological - Knowledge* also refer to this outcome.

Finally, the Black Hole effect (*Physiological - Illusion*) affected function **Establish visual contact with the runway** through the CPC *Number of goals and conflict resolution*, since it made the crew assume erroneous visual reference with the terrain.

5.2.1 Aggregated Human Factors

After having identified the potential Human Factors affecting the *human* functions in each occurrence, a comparative analysis has been performed between them, producing the aggregated Tables 20 and 21.

First, table 20 shows for each occurrence the CPCs associated to the *common functions* identified in Section 5.1. Only *human* functions have been listed, when applicable.

It can be seen that not all the *human common functions* have been influenced by a CPC which made them vary. Indeed, only three have in at least one occurrence. Such functions are **Hand over the A/C to TWR, Monitor approach path** and **Establish visual contact with the runway.**

Functions	Oslo occurrence (LN-KKL)	Cagliari occurrence (OE-FAN)	Greenland occurrence (DCBNA)
Hand over the A/C to TWR	Quality of communication	Quality of communication	-
Make approach briefing	-	-	-
Prepare the A/C for landing	-	-	-
Monitor approach path	Adequacy of HMI and operational support	-	-
	Conditions of work	Conditions of work	Conditions of work
	Number of goals and conflict resolution	-	-
	-	Circadian rhythm and stress	Circadian rhythm and stress
	Available time and time pressure	-	-
	-	Availability of procedures and plans	-
	Team collaboration quality	Team collaboration quality	Team collaboration quality
Establish visual contact with the runway	Training and experience	-	-
	-	Number of goals and conflict resolution	Number of goals and conflict resolution
Manually fly the A/C	-	-	-
Land safely	N/A	N/A	N/A

Table 20: Aggregated CPCs of human common functions rated *'Inadequate'* or *'Unpredictable'*

Among these, *five* CPCs have been found to be recurrent in at least 2 out of 3 events and have been highlighted in yellow:

- **Quality of communication**
  Affected function *Hand over the A/C to TWR* in both the Oslo and Cagliari incidents, where the handoff procedure was not carried out according to the highest standards, while it did not influence the Greenland case.

- **Condition of work and Team collaboration quality**
  Affected function *Monitor approach path* in all the occurrences, since they all took place at nighttime.

- **Circadian rhythm and stress**
  Affected *Monitor approach path* in only the Cagliari and Greenland accidents, since in both pilots had been on duty for long at the time of the event.

- **Number of goals and conflict resolution**
  Affected function *Establish visual contact with the runway* in the Cagliari and Greenland case, since in both events the flight crew was exposed to the Black Hole phenomenon, which affected their perception of the A/C position relative to the terrain.

Subsequently, each of these five common CPCs has been reported in Table 21 together with the associated function and the attributed Human Factors previously identified for each occurrence.

Six Human Factors have been found to be recurrent among the different events:

- **Interaction - Liveware/Liveware - Oral communication (Readback, Hearback / Misinterpretation)**
  Present in both the Oslo and Cagliari occurrences, affecting the communication between the APP controller and the crew. Despite being different specific HFs, the belonging HF macro-category (Oral communication) is the same.

- **Interaction - Liveware/Environment - Other factors**
  Present in all the occurrences since they all took place at nighttime.

- **Individual - Physiological - Fatigue (Duty)**
  Present in the Cagliari and Greenland cases, stemming from the excessive duty time of the flight crew at the time of the event.

- **Individual - Psychological - Attitudes/moods (Overconfidence)**
  Present in all the occurrences, refers to the possible attitude of the flight crew which would have impacted their decision-making process. In this regard, the high

amount of pilots' flight hours would be a triggering factor rather than a possible barrier.

- **Individual - Psychological - Attitudes/moods (Complacency)**
  Present in all the occurrences, refers to the possible attitude of the flight crew which would have impacted their surveillance role over each other. In this regard, the high amount of pilots' flight hours would be a triggering factor rather than a possible barrier.

- **Individual - Physiological - Illusion - Visual (Black Hole)**
  Present in the Cagliari and Greenland accidents since the respective flight crews were both exposed to such phenomenon.

Finally, the Human Factors which contributed to the dampening produced by function *Establish visual contact with the runway* in the Oslo case (through CPC *Training and experience*) have also been reported (green), to underline how HFs may affect the same function with both positive and negative outcomes.

<table>
<tr><th>Function</th><th>Common CPC</th><th>Oslo occurrence (LN-KKL)</th><th>Cagliari occurrence (OE-FAN)</th><th>Greenland occurrence (DCBNA)</th></tr>
<tr><td rowspan="3">Hand over the A/C to TWR</td><td rowspan="3">Quality of communication</td><td>Individual - Psychological - Attitude/moods (Expectations-False hypothesis)</td><td>-</td><td>-</td></tr>
<tr><td>Interactions - L - L - Oral communication (Readback,Hearback)</td><td>Interactions - L - L - Oral communication (Misinterpretation)</td><td>-</td></tr>
<tr><td>Interactions - L - H - Equipment</td><td>-</td><td>-</td></tr>
<tr><td rowspan="5">Monitor approach path</td><td rowspan="2">Conditions of work</td><td>Interactions - L - E - Other factors</td><td>Interactions - L - E - Other factors</td><td>Interactions - L - E - Other factors</td></tr>
<tr><td>Interactions - L - E - Weather</td><td>-</td><td>-</td></tr>
<tr><td>Circadian rhythm and stress</td><td>-</td><td>Individual - Physiological - Fatigue (Duty)</td><td>Individual - Physiological - Fatigue (Duty)</td></tr>
<tr><td rowspan="2">Team collaboration quality</td><td>Individual - Psychological - Attitudes/moods (Overconfidence)</td><td>Individual - Psychological - Attitudes/moods (Overconfidence)</td><td>Individual - Psychological - Attitudes/moods (Overconfidence)</td></tr>
<tr><td>Individual - Psychological - Attitudes/moods (Complacency)</td><td>Individual - Psychological - Attitudes/moods (Complacency)</td><td>Individual - Psychological - Attitudes/moods (Complacency)</td></tr>
<tr><td rowspan="3">Establish visual contact with the runway</td><td rowspan="2">Training and experience</td><td>Individual - Psychological - Information processing (Decision making / Judgement)</td><td>-</td><td>-</td></tr>
<tr><td>Individual - Psychological - Knowledge (Procedures)</td><td>-</td><td>-</td></tr>
<tr><td>Number of goals and conflict resolution</td><td>-</td><td>Individual - Physiological - Illusions - Visual (Black Hole)</td><td>Individual - Physiological - Illusions - Visual (Black Hole)</td></tr>
</table>

Table 21: Aggregated Human Factors of common functions with at least two mutual CPCs

5.3 Mitigation

The common Human Factors pinpointed during the aggregated analysis in Section 5.2.1 represent crucial underlying elements which may be frequently present in this particular scenario, therefore defining themselves as the ones requiring the highest attention.

This Section presents potential mitigations for such factors, found through the SHELL HF - HFACS mapping.

As described in Section 5, this is the second link involved in the mapping process between the FRAM analysis and the Human Factors identification, crucial for the practical use of this method. It enables the suggestion of corrective measures based on the description of the resulting HFACS nanocodes, benefiting from its widely accepted framework of suggesting recommendations.

The mapping used is internal to the department and is the result of multiple works carried out. [8][11][21]

Figure 5.3 shows the focus of this Section.

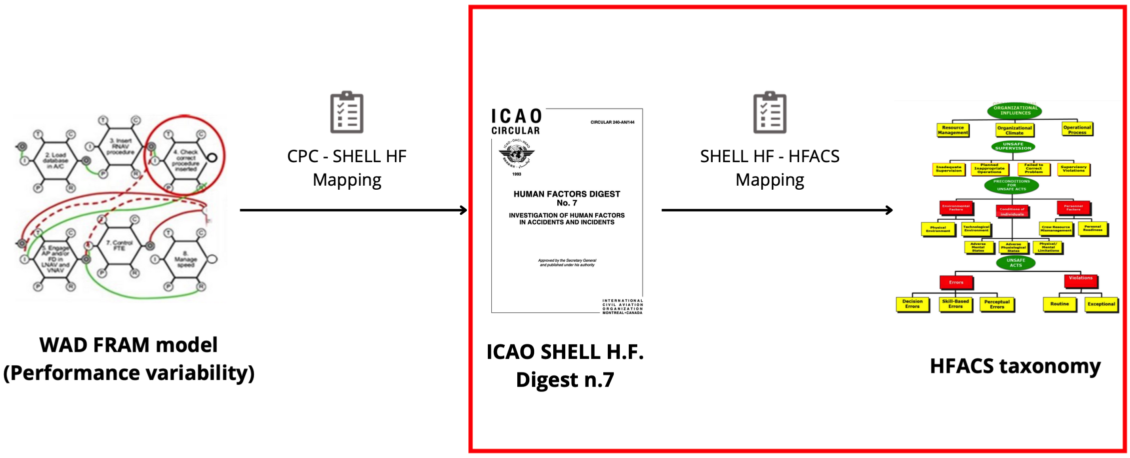


Figure 5.3: Focus of Section 5.3 - second mapping process

Table 22 shows the resulting mapping for those HF found to be recurrent throughout the occurrences analyzed. The HF positively contributing to the dampening of variability in the Oslo case were also mapped to their respective HFACS nanocodes and are represented in green.

ICAO HF		HFACS
Macro	**Sub-category**	
Individual - Physiological - Illusions - Visual	Black Hole	AE301 ERROR DUE TO MISPERCEPTION
Individual - Psychological - Attitudes/moods	Overconfidence	PC206 OVERCONFIDENCE
	Complacency	PC208 COMPLACENCY
Individual - Psychological - Information processing	Decision making / Judgement	AE2XX JUDGEMENT AND DECISION MAKING ERRORS
Individual - Psychological - Knowledge	Procedures	AE103 PROCEDURAL ERROR
Interactions - L - L - Oral communication	Readback, Hearback	PP108 CHALLENGE AND REPLY
	Misinterpretation	PP112 MISCOMMUNICATION
Interactions - L - E - Other factors	Time of day	PE102 VISION RESTRICTED BY METEO CONDITIONS
Individual - Physiological - Fatigue	Duty hours	PC306 FATIGUE (PC307)

Table 22: SHELL HF - HFACS mapping

The following list reports the official nanocodes description. [24] [25]

- **AE301 ERROR DUE TO MISPERCEPTION**
  Error due to misperception is a factor when an individual acts or fails to act based on an illusion, misperception or disorientation state and this act or failure to act creates an unsafe situation.
- **PC206 OVERCONFIDENCE**
  Overconfidence is a factor when the individual overvalues or overestimates personal capability, the capability of others or the capability of aircraft/vehicles or equipment and this creates an unsafe situation.
- **PC208 COMPLACENCY**
  "Complacency is a factor when the individual's state of reduced conscious attention due to an attitude of overconfidence, undermotivation or the sense that others "have the situation under control" leads to an unsafe situation."
- **PP108 CHALLENGE AND REPLY**
  Challenge and reply is a factor when communications did not include supportive feedback or acknowledgement to ensure that personnel correctly understand announcements or directives.

- **PP112 MISCOMMUNICATION**
  Miscommunication is a factor when correctly communicated information is misunderstood, misinterpreted, or disregarded.
- **PE102 VISION RESTRICTED BY METEO CONDITIONS**
  Vision restricted by meteorological conditions is a factor when weather, haze, or darkness restricted the vision of the individual to a point where normal duties were affected.
- **PC307 FATIGUE - PHYSIOLOGICAL/MENTAL**
  Fatigue - Physiological/Mental is a factor when the individual's diminished physical or mental capability is due to an inadequate recovery, as a result of restricted or shortened sleep or physical or mental activity during prolonged wakefulness. Fatigue may additionally be described as acute, cumulative or chronic.

The following nanocodes have been reported in their *positive version*, as they positively affected the associated function in the Oslo case.

- **AE2XX JUDGEMENT AND DECISION MAKING BARRIERS**
  Are *barriers* in a mishap when behavior or actions of the individual proceed as intended *and* the chosen plan proves *adequate* to achieve the desired end-state and results in a *safe* situation.
- **AE103 PROCEDURAL BARRIER**
  Is a *barrier* when a procedure is accomplished in the *right* sequence or using the *right* technique or when the *right* control or switch is used. Procedural *barriers* also *prevent* errors in navigation, calculation or operation of automated systems.

This highlights how Human Factors should not be seen as only generating adverse outcomes, but also as barriers acting on human performance.

Finally, it is worth mentioning that in Section 5.1, function *Monitor signals and terrain* was found to be *highly* contributing to the propagation of variability. However, this function is of type Technological, therefore potential mitigation actions must be studied with the help of other methodologies, specific for such category.

6 Conclusions

This project has been focused on outlining the analysis performed on three occurrences taking place during the approach phase in Oslo Gardermoen, Cagliari Elmas and Narsarsuaq, sharing similar features among them. The goal was to present the specific method implemented, describing the different phases followed and the tasks performed, as well as the results obtained.

Such method enables the study of performance variability across different occurrence functions, in order to identify commonalities among them. This, in turn, validates the analysis conducted and helps pinpoint those human factors which might play a crucial role in the specific scenario, with the ultimate goal of suggesting mitigations to improve flight safety.

The workflow followed started with the gathering and selection of the data regarding different incidents and accidents, in order to find those exhibiting the proper similar features to be compared. Then, the analysis of each single event has been performed and the results shown.

Finally, a comparative analysis has been performed between the different cases, describing the commonalities discovered and those aspects which were found to be recurrent. This included common functions and shared ICAO Human Factors. This eventually led to the identification of potential mitigations through the SHELL HF - HFACS mapping, exploiting the nanocodes description as a source of generally accepted recommendations.

The methodology implemented for conducting the analysis of each occurrence has been the Functional Resonance Analysis Method (FRAM). Based on the Safety-II principles, FRAM enables the analysis of complex non-linear socio-technical systems and the interactions within it, which could result harder if carried out uniquely with traditional methods based on a more proportional logic.

FRAM produces two different models of the event analyzed, namely the *Work-As-Imagined* and the *Work-As-Done*. These enable to highlight the differences between what should potentially happen in theory and what actually happens in a real-life scenario.

Such difference stems from a fundamental assumption of the method which is the fact that workers are exposed to an underspecified system which forces them to continuously adapt their daily performance, generating that intrinsic variability which, through the connections established, propagates among the different functions of a system making the overall variability vary as well.

When it exceeds a certain threshold (the *resilience* of the system), it diverges and causes a negative outcome. FRAM is therefore capable of modeling these peculiar aspects.

The comparative analysis returned interesting results. The functions which turned out to be always present, and caused the associated human function to vary in all the occurrences, were **Monitor approach path**, **Establish visual contact with the runway** and **Hand over the A/C to TWR**. Of these, only the first *highly* contributed, on average, to the propagation of variability through the system, shaping itself as the most critical function of all the cases studied. Moreover, through the study of the relative CPCs, the Human Factors affecting these three functions have been identified. Several of them were found to be common across the different occurrences, therefore becoming the most crucial to be addressed. Mitigations have, indeed, been assessed for such Human Factors.

In conclusion, it is worth mentioning the areas where this method could be improved.

It goes without saying that every occurrence represents a unique event, with its own characteristics and features, therefore a proper comparison level could be difficult to establish when selecting the events to analyze and compare. Moreover, a certain degree of subjectivity still remains throughout the process, especially during the Human Factors selection at the end of the analysis, which may be questioned for its validity. In addition, the choice was based on a mapping with FRAM CPCs, which could be improved or even re-designed for this specific purpose.

This notwithstanding, the main benefits introduced by this method represent substantial features which may pave the way to a new way of analysis in the future. The central aspect is the possibility of 'retracing' the steps followed in a pragmatic and sequential way, such that the final Human Factors selection is backed by a rigorous process leading to their identification, reducing, even if not completely, the subjectivity of the analyst. Other investigators could, therefore, follow along the inductive steps, correcting or confirming the reasoning process without the need to guess the choices made.

Moreover, this method allows the self-validation of the analysis since, by comparing it with similar occurrences, the results obtained could be proven acceptable or not.

Finally, the identification of shared underlying Human Factors may help pinpoint the most critical areas to be addressed with the highest priority through mitigation actions, always with the ultimate goal of improving the flight safety of the aviation world.

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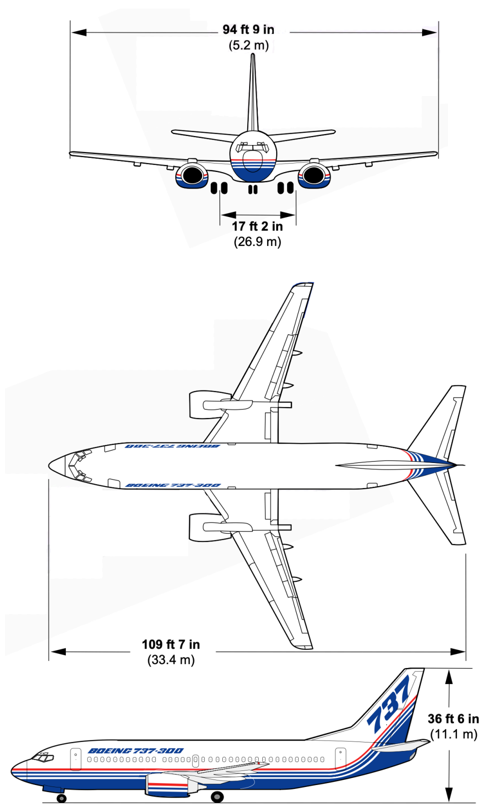
Appendix A

Boeing 737-300 - Technical Data

The Boeing 737-300 is the first variant of the *Classic* series, developed from 1979 with its maiden flight taking place on February 1984, replacing the B737-200 Advanced. With respect to it, the 300 series presents several improvements regarding aerodynamic, structures, cockpit and cabin interiors developed for the B757/B767 series. (Data:[3][22])

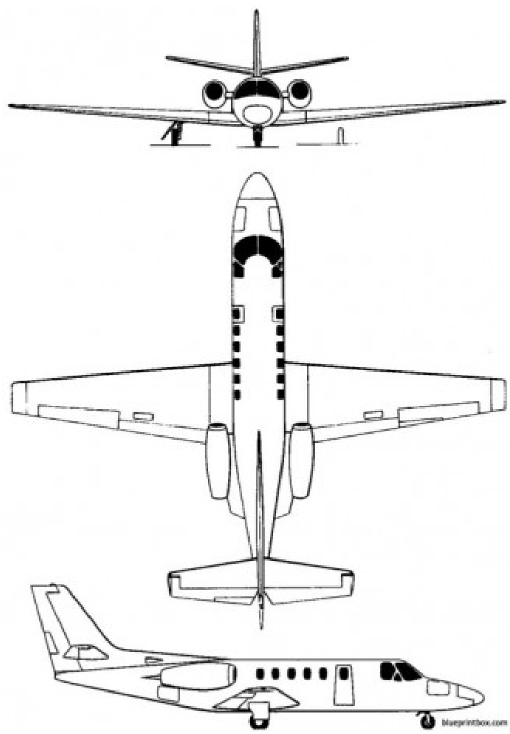
Crew & Passengers	
Pilots	2
Max Passengers	149 (1 Class)
Dimensions	
Length	33,40 m
Height	11,15 m
Wingspan	28,88 m
Wing Area	91,0 m^2
Sweep	25°
Fuselage diameter	3,76 m
Weights	
OEW	32 820 kg
MTOW	62 820 kg
MLW	52 880 kg
Max payload	16 890 kg
Cargo capacity	30,2 m^3
Fuel capacity	20 100 L
Performance	
Cruise speed	0,75 Mach (926,10 km/h)
Max speed	0,82 Mach (1 012,54 km/h)
Max range	4 175 km
Service ceiling	37 000 ft (11 275 m)
Engines	
Engines (x2)	CFM 56-3C-1
Thrust (x2)	98 kN



Cessna 500 Citation I - Technical Data

The Cessna 500 Citation I is the first business jet of the Citation series, produced by Cessna from 1969. It was at first certified as Citation 500 and later upgraded as Citation I in 1976. Its production ended in 1985. (Data:[4])

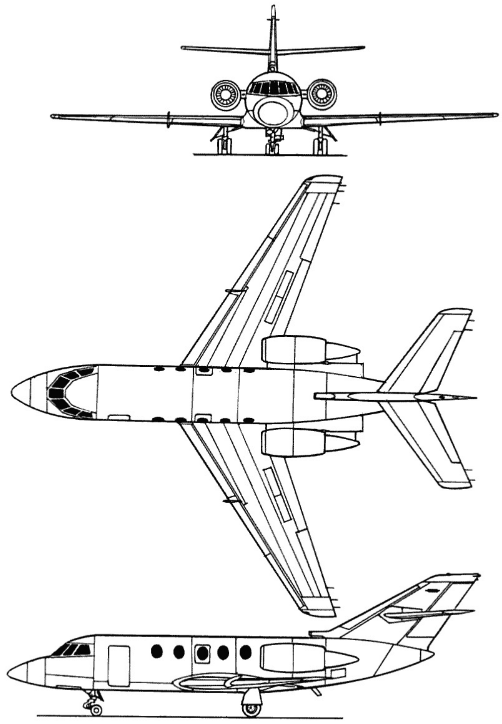
Crew & Passengers	
Pilots	2
Max Passengers	5
Dimensions	
Length	13,26 m
Height	4,37 m
Wingspan	14,35 m
Wing Area	25,87 m^2
Aspect ratio	7,83
Weights	
OEW	3 008 kg
MTOW	5 375 kg
Fuel capacity	2 130 L
Performance	
Cruise speed	357 Kts (661 km/h)
Max speed	Mach 0,705
Stall speed	82 Kts (152 km/h)
Max range	2,459 km
Service ceiling	41 000 ft (12 000 m)
Rate of Climb	2,719 ft/min
Engines	
Engines (x2)	Pratt & Whitney Canada JT15D-1B
Thrust (x2)	9,8 kN



Dassault Falcon 20 - Technical Data

The Falcon 20 is the first business jet produced by the French Dassault Aviation, as a result of a collaboration with the French Government. Produced between 1965 and 1991, it is the first of the Falcon series, with two more variants later produced directly derived from it. (Data:[5])

Crew & Passengers	
Pilots	2
Max Passengers	8-14
Dimensions	
Length	17,15 m
Height	5,32 m
Wingspan	16,30 m
Wing Area	41,00 m^2
Aspect ratio	6,4
Weights	
OEW	7 530 kg
MTOW	13 000 kg
Fuel capacity	5 200 L
Performance	
Cruise speed	400 Kts (750 km/h)
Max speed	465 Kts (862 km/h)
Stall speed	82 Kts (152 km/h)
Max range	3 350 km
Service ceiling	42 000 ft (12 800 m)
Engines	
Engines (x2)	General Electric CF700-2D-2
Thrust (x2)	20 kN



Appendix B

Cagliari accident functions tables

Name of function	C.1. Make approach briefing
Description	The flight crew reviews the approach procedures, highlighting important features (minimums, restrictions, etc.) and preparing to adopt contingency measures if needed
Aspect	Description of Aspect
Input	A/C cleared for ILS approach
Output	Crew ready for the approach
Precondition	
Resource	
Control	
Time	

Name of function	C.2. Ask for visual approach
Description	The flight crew asks the controller the clearance to conduct a visual approach
Aspect	Description of Aspect
Input	A/C cleared for ILS approach
	Crew ready for the approach
Output	Visual approach requested
Precondition	
Resource	
Control	
Time	

Name of function	C.3. Prepare the A/C for landing
Description	The flight crew sets the A/C for landing (flaps, speedbrakes, FMS etc.)
Aspect	Description of Aspect
Input	Crew ready for the approach
Output	A/C ready for the approach
Precondition	
Resource	
Control	
Time	

Name of function	C.4.Establish visual contact with the runway
Description	The flight crew looks outside the windshield to establish a visual contact with the runway
Aspect	**Description of Aspect**
Input	Runway in sight and separation asked
Output	Runway and terrain in sight
Precondition	
Resource	
Control	
Time	

Name of function	C.5. Monitor approach path
Description	The flight crew monitors the A/C's descend path, checking the correspondace with the designated one and verifying the separation from terrain obstacles and nearby traffic
Aspect	**Description of Aspect**
Input	A/C cleared for visual approach
	A/C ready for the approach
	Crew ready for the approach
Output	Approach path monitored
Precondition	
Resource	
Control	
Time	

Name of function	C.6. Manually fly the A/C
Description	The Pilot Flying (PF) takes over the control of the A/C and manually flies the visual approach to the runway
Aspect	**Description of Aspect**
Input	A/C cleared for visual approach
Output	A/C manually flown
Precondition	A/C cleared to land
Resource	
Control	Approach path monitored
	A/C on TWR frequency
Time	

Name of function	C.7. Land safely
Description	The landing sequence si completed and the A/C performs a safe touchdown on the runway
Aspect	Description of Aspect
Input	A/C manually flown
Output	
Precondition	
Resource	
Control	
Time	

Name of function	ATC.1. Give ILS approach clearance
Description	The APP controller outlines a landing sequence and gives ILS clearance accordingly
Aspect	Description of Aspect
Input	
Output	A/C cleared for ILS approach
Precondition	
Resource	
Control	
Time	

Name of function	ATC.2. Ask to report runway and terrain in sight
Description	The APP controller asks the crew to report when they have the runway in sight and if they are able to maintain visual separation with the terrain
Aspect	Description of Aspect
Input	Visual approach requested
Output	Runway in sight and separation asked
Precondition	
Resource	
Control	
Time	

Name of function	ATC.3. Give clearance for visual approach
Description	The APP controller clears the A/C to conduct a visual approach
Aspect	Description of Aspect
Input	Runway in sight and separation asked
Output	A/C cleared for visual approach
Precondition	Runway and terrain in sight
Resource	
Control	
Time	

Name of function	ATC.4. Hand over the A/C to TWR
Description	The APP controller initiates the handoff procedure transferring the responsability for the A/C to the TWR controller
Aspect	Description of Aspect
Input	A/C cleared for visual approach
Output	A/C on TWR frequency
Precondition	
Resource	
Control	
Time	

Name of function	ATC.5. Give landing clearance
Description	The TWR controller clears the A/C for landing ensuring the runway is available for a safe touchdown
Aspect	Description of Aspect
Input	A/C on TWR frequency
Output	A/C cleared to land
Precondition	
Resource	
Control	
Time	

Appendix C

Greenland accident functions tables

Name of function	C.1. Start the descend
Description	The A/C starts its descend from cruise
Aspect	Description of Aspect
Input	
Output	A/C descending
Precondition	
Resource	
Control	
Time	

Name of function	C.2 Make approach briefing
Description	The flight crew reviews the approach procedures, highlighting important features (minimums, restrictions, etc.) and preparing to adopt contingency measures if needed
Aspect	Description of Aspect
Input	A/C descending
Output	Approach briefing confirmed
Precondition	
Resource	
Control	
Time	

Name of function	C.3. Prepare the A/C for landing
Description	The flight crew sets the A/C for landing (flaps, speedbrakes, FMS etc.)
Aspect	Description of Aspect
Input	Approach briefing confirmed
Output	A/C ready for the approach
Precondition	
Resource	
Control	
Time	

Name of function	C.4. Monitor approach path
Description	The flight crew monitors the A/C's descend path, checking the correspondace with the designated one and verifying the separation from terrain obstacles and nearby traffic
Aspect	**Description of Aspect**
Input	Approach briefing confirmed
Output	Approach path monitored
Precondition	
Resource	
Control	
Time	

Name of function	C.5. Perform SOPs and checklist
Description	The flight crew goes through the necesary checklists while performing the required SOPs to ensure safety and efficiency
Aspect	**Description of Aspect**
Input	Approach briefing confirmed
Output	SOPs and checklist performed
Precondition	
Resource	
Control	
Time	

Name of function	C.6. Establish visual contact with the runway
Description	The flight crew looks outside the windshield to establish a visual contact with the runway before the minimum altitude is reached
Aspect	**Description of Aspect**
Input	A/C stable on the path
Output	Runway in sight
Precondition	
Resource	
Control	
Time	

Name of function	C.7. Manually fly the A/C
Description	The Pilot Flying (PF) takes over the control of the A/C and manually flies the remaining part of the approach and landing, if and when the proper operational conditions are met
Aspect	Description of Aspect
Input	Runway in sight
Output	A/C manually flown
Precondition	Area informations given
Resource	Flags and alarms in the cockpit
Control	Approach path monitored
	SOPs and checklist performed
Time	

Name of function	C.8. Land safely
Description	The landing sequence si completed and the A/C performs a safe touchdown on the runway
Aspect	Description of Aspect
Input	A/C manually flown
Output	
Precondition	
Resource	
Control	
Time	

Name of function	ATC.1. Hand over the A/C to AFIS
Description	The APP controller initiates the handoff procedure, transferring the separation responsability directly to the flight crew and instructing them to contact the AFIS controller
Aspect	Description of Aspect
Input	A/C descending
Output	A/C on AFIS frequency
Precondition	
Resource	
Control	
Time	

Name of function	ATC.2. Establish visual contact with the A/C
Description	The AFIS controller looks outisde to monitor the arriving/departing A/Cs and informs the pilots about traffic nearby
Aspect	Description of Aspect
Input	A/C on AFIS frequency
Output	Controller looking for A/C
Precondition	
Resource	
Control	
Time	

Name of function	ATC.3. Report tfc, rwy and weather status
Description	The AFIS controller informs the crew about the current conditions of the airspace around the field
Aspect	Description of Aspect
Input	A/C on AFIS frequency
Output	Area informations given
Precondition	
Resource	
Control	
Time	Controller looking for A/C

Name of function	S.1. Monitor signals and terrain
Description	The avionic system monitors the integrity of the NAV signals received and the terrain ahead, generating flags and alarms in the cockpit to alert the crew and disconnecting the AP if needed
Aspect	Description of Aspect
Input	A/C descending
Output	Flags and alarms in the cockpit
Precondition	
Resource	
Control	
Time	

Name of function	S.2. Fly following the horizontal NAV signal
Description	The A/C follows the horizontal NAV signal ensuring a precise directional guidance to the runway
Aspect	**Description of Aspect**
Input	A/C ready for the approach
Output	A/C stable on the path
Precondition	
Resource	Flags and alarms in the cockpit
Control	Approach path monitored
	SOPs and checklist performed
Time	