Agent-Based Simulation of Flight TK1951 Crash Landing on Final Approach to Amsterdam Schiphol Airport

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Challenge the future

Agent-Based Simulation of Flight TK1951 Crash Landing on Final Approach to Amsterdam Schiphol Airport

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LIST OF ABBREVIATIONS

737NG	737 New Generation
A/P	Auto-Pilot
A/T	Auto-throttle
ABM	Agent-Based Modeling
ABMS	Agent-Based Modeling and Simulation
ADC	Air Data Computer
ADIRS	Air Data Inertial Reference System
ADIRU	Air Data Inertial Reference Unit
ADM	Air Data Module
AFDS	Auto-Pilot Director System
AFS	Automatic Flight System
AGL	Above Ground Level
AGS	Air/Ground System
AOA	Angle of Attack
AOC	Airline Operation Center
APP	Approach
ATC	Air Traffic Control
ATCo	Air Traffic Contoller
ATL	Above Terrain Level
AVI	Aviate
AWM	Aural Warning Module
CAT	Category
CDU	Command Display Unit
CFIT	Controlled Flight into Terrain
CNS	Communication Navigation Surveillance
COM	Communicate
DEG	Degree
DSB	Dutch Safety Board
dt	Delta time
EASA	European Aviation Safety Agency
EFIS	Electronic Flight Instrument System
EGPWS	Enhanced Ground Proximity Warning System
EICAS	Engine Indicating and Crew Alerting System
Ex. Tr.	External Trigger
F/D	Flight Director
FAA	Federal Aviation Administration
FCC	Flight Control Computers
FDU	Flight Display Unit
FMA	Flgiht Mode Annuciation

FMC	Flight Management Computer
FMCW	Frequency Modulated Continuous Wave
FPM	Feet per Minute
ft	Feet
ft/min	Feet per Minute
G/S	Glide slope
GA	Go-Around
GPS	Global Positioning System
GWPS	Ground Proximity Warning System
HMI	Human Machine Interface
HUD	Head Up Display
hz	Hertz
ILS	Instrument Landing System
INS	Inertial Navigation System
IRU	Inertial Reference Unit
ISDU	Inertial System Display Unit
L.H.	Likelihood
LIFUS	Line Flying Under Supervision
LNAV	Lateral Navigation
LOC	Localizer
LRRA	Low Range Radio Altimeter
M	Meter
MAS	Multi-Agent System
MA-SA	Multi-Agent Situation Awareness
MAWS	Mach/Airspeed Warning System
MCP	Mode Control Panel
MFD	Multi-Functional Display
MIS	Miscellaneous
MSc	Masters
MTRS	Metric System
NASA	National Aeronautics and Space Administration
NAV	Navigate
NCD	Non-Computed Data
ND	Navigation Display
NLR	Nederlands Lucht- en Ruimtevaartcentrum
NM	Nautical Mile
OPP	Opportunistic control mode
PF	Pilot Flying
PFD	Primary Flight Display
PNF	Pilot Not Flying
PSEU	Proximity Switch Electronic Unit
R/T	Radio Transmission
RA	Radio Altitude
SA	Situation Awareness
SMYD	Stall Management Yaw Damping

SP	Safety Pilot
STAR	Standard Arrival Route
SWS	Stall Warning System
TA	Take-Off
TAC	Tactical control mode
TCAS	Traffic Alert and Collision Avoidance System
TU-Delft	Technical University of Delft
V/S	Vertical Speed
VHF	Very High Frequency
VOR	VHF Omnidirectional Range
WS	Warning System
$\boldsymbol{\varepsilon}$	Probability of Error
$\boldsymbol{\chi^O}$	1 if task is done at Opportunistic mode. Zero otherwise.
$\boldsymbol{\chi^T}$	1 if task is done at Tactical mode. Zero otherwise.

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PREFACE

This report is the final step in concluding my studies as a student in Aerospace Engineering at the Delft University of Technology in the Netherlands. Studying in Delft was a challenging but yet pleasant experience for me, and I truly enjoyed the opportunity to conclude my studies with a research in my field of interest, Air Transport Operation and Safety .

The report focuses on the crash of Turkish Airlines Flight TK1951, that occurred at the vicinity of Amsterdam Schiphol airport in February 2009. Through an agent-based analysis of the operation, combined with a simulation of task development and human behavior, I had the opportunity to re-analyze the formation of the event and investigate the sensitivity of the outcome of the operation to multiple possible deviations.

I would like to thank my supervisors, prof. dr. H.A.P. Blom, and dr. ir. M.M. van Paassen, for their dedicated and valuable guidance throughout the project. I was lucky and proud to have them as my supervisors and learned a lot from their constructive feedback throughout the project. I would also like to thank dr. ir. E. van Kampen for joining the assessment committee of my defense presentation.

I would also like to thank my previous instructors throughout my studies in Delft, for the possibility to learn all I have about the fascinating world of aerospace industry. Last, but not least, I would like to thank all my family and friends for their support throughout the previous years. Thank you all!

Hossein Jaberi
Delft; August 23, 2017

SUMMARY

Flight TK1951 was a commercial passenger flight, flying towards Amsterdam International Schiphol Airport. During the final approach, a malfunctioning radio altimeter triggered a specific event sequence that led to an early activation of the 'Retard Flare' mode of the autothrottle. The crew failed to observe the incorrect mode of the autothrottle, and the subsequent decrease of airspeed in time, leading to the stall of the aircraft. The aircraft had, however, previously been flown successfully, with the same malfunctioning equipment. The report aims at providing a better understanding of why the event sequence of Flight TK1951 led to a crash, while the previous flights did not? What prevented the crew of Flight TK1951 from reacting to the occurrences sufficiently and on-time?

Through a coupling of agent-based modeling and an application of Hollnagel's Contextual Control theory, the crew's performance rate at different levels of comfort and control is assessed. The operation is modeled through its constituting agents, consisting of both human and system agents, along with specific task clusters of human agents, through which the crew must react to any arising conflicts. Subsequent simulation presents, for any unit drop in crew's control mode, how the crew's ability in observing, comprehending and projecting the available data to any potential crisis changes. In addition, the simulation also details how a lower control mode influences the ability of Pilot Not Flying in providing real-time feedback to the Pilot Flying, increasing the probability of making irreversible errors.

The report evaluates the operation under the explicit assumption of a conventional crew composition, consisting of a Pilot Flying and a Pilot Not Flying. This is in contrast to the actual cockpit crew composition of Flight TK1951, in which a Safety Pilot was also present in the cockpit. This is done with the purpose of eliminating the decisive contributions of a non-conventional crew composition to the operation, identified in the official investigation report.

Based on the understanding of crew's performance rates at different control modes, a success likelihood probability of the operation is assessed. In order to show the possible consequences on a successful completion of the operation, various alternatives to the actual event sequence are studied. The agent-based simulation results help visualize how the short line-up procedure can further tighten the crew's time horizon, given a scenario in which the crew's performance is jeopardized by a hazard that occurred prior to interception of the glide path.

The simulation results indicate that, compared to a scenario with a single faulty radio altimeter, more extreme changes are enforced on the event sequence and subsequent taskload density, following the coupling of a short line-up to the approach scenario with or without a faulty altimeter. The analysis of crew's taskload indicated that, as a result of a short line-up, the pilot's performance is reduced to an opportunistic level throughout the final crucial moments of the approach. As such, the pilot's response rate is reduced significantly, allowing for higher probabilities of catastrophic mistakes.

1

INTRODUCTION

"Nothing can be absolutely free from risk...
Consequently nothing can be absolutely safe."

Geoffrey Taylor[1]

The rapid growth of commercial aviation highlights the necessity of a continuous improvement of safety measures. Learning from previous incidents and implementing design improvements accordingly remains as key elements to the future of aviation. However, it will never be possible to fully prepare and pre-plan for all possible combinations of hazardous conditions. To better understand this statement, and for the purpose of the analysis in this report, the fairly recent fatal accident of Turkish Airlines Flight TK1951[2] is studied in details. A Boeing 737-800 aircraft crash landed during its final approach to Amsterdam International Schiphol Airport[3], onto a field located only 1.5 kilometers short of the threshold of Runway 18R. The crash was stated to have occurred following a sequence of events which resulted in loss of airspeed to the point of stall, initiated by the malfunctioning of one of the measurement systems of the cockpit responsible for computing the height above the ground. Unnoticed by the flight crew, this resulted in an early activation of the 'Retard Flare' mode of the Autothrottle (A/T), after which the aircraft stalled and crashed prior to reaching the airport. The same aircraft, however, had been flying numerous times with the same faulty component installed on-board. Why is it that such non-ideal condition could lead to a catastrophic accident in some cases, and not in others? Is it a matter of bad luck only, or is there a more logical explanation behind it?

This report aims at answering the above mentioned questions, with an objective of describing the sensitivity of the operation to potential variations in the event sequence and in the performance rate of its constituting elements. The event sequence experienced on Flight TK1951 is reconstructed, and crew's respective tasks are identified, in order to assemble a reference scenario of the landing aircraft. In

[1] (G. Taylor and Hegney, 2004)
[2] For the remainder of this report, Turkish Airlines Flight TK1951 is referred to as Flight TK1951.
[3] For the remainder of this report, the Amsterdam International Airport Schiphol is referred to as Schipol airport.

order to recognize all factors that could potentially influence the operation, an agent-based modeling approach is used to break down the operation into its constituting agents.

Using Hollnagel's Contextual Control theory (Hollnagel, 1993), the performance of human agents are modeled under different levels of workload intensities. This will help simulate the degree to which they could have fulfilled their tasks, given the specific event sequence. Next, qualitative and quantitative assessments of crew's performance are conducted, through which numerous variations of the reference operation are simulated, and the corresponding influences on the performance rates of the crew are studied. The outcome of the simulations will assist in understanding the factors with the most significant contributions to the formation of the operation and will.

The report is organized as follows. First, Chapter 2 provides a detailed description of the operation under analysis. In addition, the conditions of Flight TK1951 is also briefly outlined in this chapter. Next, Chapter 3 introduces the concept of Agent-Based Modeling, in which the agents contributing to the formation of the approach of a flight and their relations are identified. This is followed by a modeling of the performance of the human agents in Chapter 4, for which the Hollnagel's Contextual Control theory is introduced and applied. Through a coupling with ABM, the crew's performance at different modes of control is analyzed. Chapter 5 will next describe and represent the results of a quantitative assessment of the safety of the operation. The report is concluded in Chapter 6.

2

OPERATION

For modeling purposes of this report, the final phase of a landing flight prior to touching down on the designated runway is considered, namely the final approach. This chapter provides a basic description of the operation procedure during this phase of the flight, along with a description of the occurrences specific to Flight TK1951.

First, Section 2.1 provides a general description of a standard final approach. Section 2.2 next describes the event sequence that took place on Flight TK1951, briefly outlining the deviations experienced compared to the standard approach of Section 2.1. This is followed by an overview of the most significant findings of the official investigation report, presented in Section 2.3.

2.1. STANDARD FINAL APPROACH

In order to better understand the event sequence during the final approach of Flight TK1951, one should first obtain a clear understanding of a standard approach. This will help better understand the procedure deviations that occurred during Flight TK1951.

As it can be seen in Figure 2.1, an approach of an aircraft consists of several segments, each with dedicated steps to be completed. The scope of the operation considered here initiates from the point in time at which the crew of the incoming aircraft, flying on predefined radar vectors, are guided by the ground controller regarding their arrival route. While continuously monitoring the traffic, the Air Traffic Controller (ATCo) communicates to and updates the flight crew's awareness of the specific Standard Arrival Route (STAR) to be followed by the crew. The ATCo and the flight crew will use the available means of air-ground communication to raise awareness over any possible concerns regarding the communicated STAR.

Upon confirmation of the route by the crew, the aircraft is configured to follow the designated STAR towards the runway. Regarding the operation, an Instrument Landing

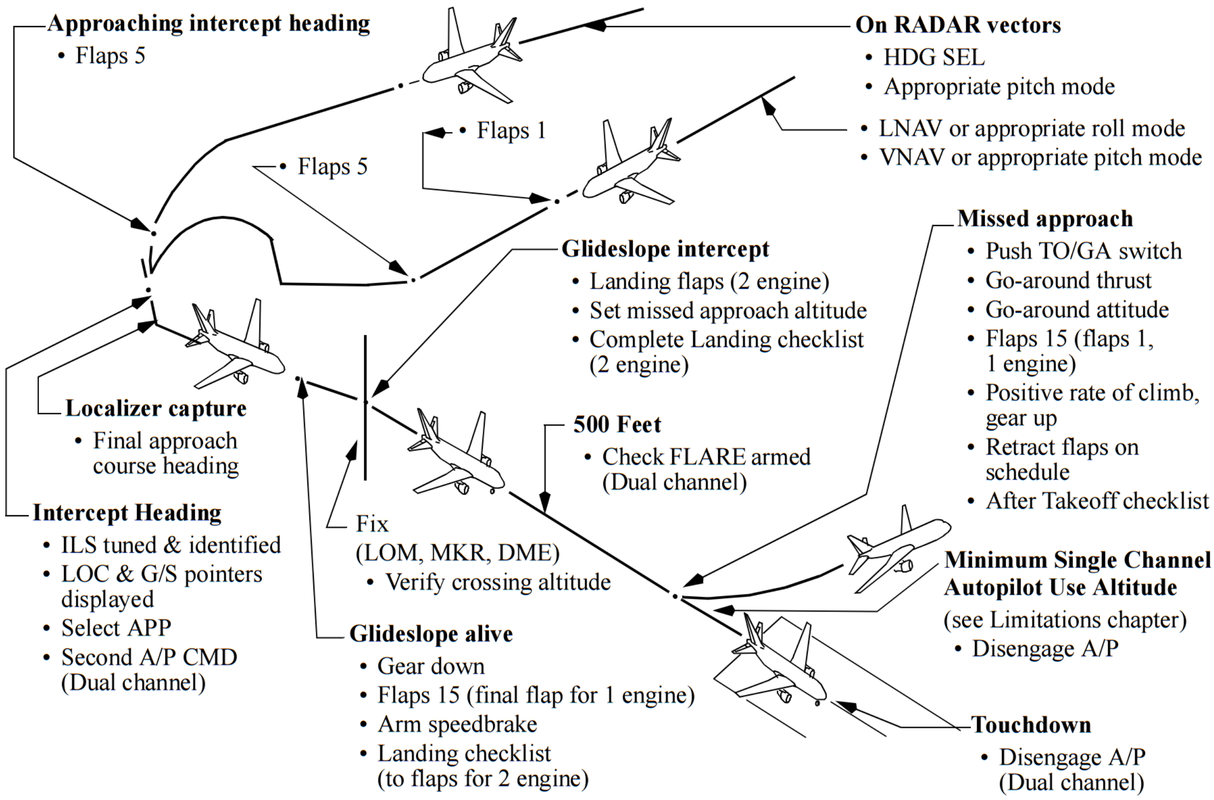

Figure 2.1: Procedure overview of an ILS approach (Boeing, 2008)

System (ILS) approach is considered for this report. This system, fully available at Schiphol airport on the day of Flight TK1951, can be used for structuring the event sequence and modeling of both a standard approach and for Flight TK1951. The aircraft's ILS receivers, once in the range of the ILS, receive the VHF/UHF radio signals transmitted by the ground-based ILS radio beam transmitter (Borst and Mulder, 2015-2016b). These radio signals provide the aircraft with horizontal and vertical guidance during its approach towards the designated runway, in addition to providing, at fixed points, the distance to the reference point of landing (ITU, 2012).

As it can be seen from Figure 2.1, following the STAR and further instructions issued by the ATCo, the aircraft is directed towards capturing the localizer and the glide slope signals, the two separate radio signals transmitted by the ground ILS transmitter. Prior to intercepting any of the two ILS signals, the flight crew will have to adjust their cockpit instruments to tune in the relevant ILS frequency and arm their ILS equipment, such that ILS signals can be received and processed on-board. First, the localizer signal is captured, which puts the aircraft on the final approach course heading, a heading identical to that of the designated runway. Next, the glide slope signal is intercepted, which locates the aircraft on a 3 *degree* descend path towards the runway threshold. In the meantime, there remains various tasks regarding aircraft configurations, checklists and systems monitoring to be executed by the crew, to ensure a smooth and safe descend.

Having achieved horizontal and vertical alignments with the runway, a crucial point prior to the final touch down is with regards to a decision point in which the crew should assess the possibility of a continued approach and landing under the current flight conditions. A general rule, also included in Turkish Airlines' Standard Operating Procedures (Airbus, 2006), prescribes that for an aircraft flying at insufficient visibility, and while not yet fully configured for landing at the time of reaching an altitude of 1,000 ft, the approach should be aborted (Dutch Safety Board, 2010). The crew should issue a go-around, and contact the ATCo for a second attempt at landing on the runway. This will require a reconfiguration of the aircraft.

In the event of a well-stabilized approach, the aircraft will continue its descend on the glide slope towards the runway, and at the moment of reaching an altitude of less than 27 ft (Dutch Safety Board, 2010), the Autothrottle (A/T) is automatically reconfigured to a 'Retard Flare' mode, in which no thrust is generated, and the aircraft will flare and touch down on the runway.

It should be noted that the modeling in this report does not include the tasks related to the flare and touch down, and only considers the procedures leading to the decision point with regards to the missed approach. This is further outlined when studying the event sequence specific to Flight TK1951.

2.2. FLIGHT TK1951

Operated by Turkish Airlines, Flight TK1951 was a scheduled passenger flight to Schiphol airport in the Netherlands, originating at the Istanbul Ataturk Airport in Turkey. While on its final approach, one of the aircraft's measurement systems, used for computing the height over the terrain, was producing erroneous readings. This is believed to have initiated a chain of events leading to specific deviations from the standard approach procedures (Dutch Safety Board, 2010). This section aims at providing an overall overview of the characteristics of Flight TK1951, and the specific flight conditions experienced on this flight. The technical difficulties and corresponding crew's response will be presented here. For a more elaborated description of Flight TK1951, along with a more detailed presentation of the official findings on the formation of the events leading to the crash, the reader is requested to study Appendix A.

The aircraft, while on its final approach towards Runway 18R at Schiphol airport, stalled and crashed onto a field only one mile away from the runway. The crash had in total five fatalities, including all three pilots situated in the cockpit. Although the crew was expected to perform a routine approach to Schiphol airport, a technical failure and the subsequent system changes that remained unnoticed by the flight crew eventually led to a significant reduction of airspeed. Late and incomplete recovery procedures followed by the crew were insufficient to save the flight.

The first signs of trouble on Flight TK1951 appeared when, while flying at about 8,500 ft, the aural landing gear warning was generated, indicating the need for the crew to retract the landing gears. Anticipated by the captain as a faulty warning, the warning was disregarded and the crew continued their approach. The warning was generated for a total of five times. Instructed for an ILS landing on Runway 18R, the crew followed the instructions of the ATCo to line up with the runway and to intercept the glide slope for their final descent to the runway. However, as a result of a short line-up with the runway, the crew had to perform a sharp turn-in for the interception of the localizer. This, combined with the presence of strong winds, caused the aircraft to line up with the runway course heading at a distance of 5.5 Nautical Miles ($N.M.$) to the runway threshold. As such, while flying at an altitude of 2,000 ft, the crew had to intercept the glide slope signal had from above. Although not considered as an unusual procedure (Dutch Safety Board, 2010), this meant an extra set of actions had to be executed by the flight crew, in order to assure a smooth interception of the glide slope and a safe descend towards the runway.

While the crew was occupied with performing the tasks related to re-configuring the aircraft for the interception of the glide slope, the next unfortunate event occurred. The left Low Range Radio Altimeter (LRRA), referred to as LRRA-1, was producing erroneous Radio Altimeter (RA) output at various points during the flight, which was also responsible for the generation of the landing gear configuration warnings. The incorrect RA output was also fed into the flight's A/T, which in combination with the consequences of re-configuring the aircraft for intercepting the glide slope from above, resulted in an early activation of the 'Retard Flare' mode of the A/T. Intended for the phase preceding the touchdown (Oxford Aviation Academy, 2008), once activated, the thrust levers are moved back to their idle position and the A/T no longer controls the thrust.

The activation of the retard flare mode of the A/T remained unnoticed by the crew, who was struggling to fully understand the behavior of their systems, while flying the jet for the continuation of the approach. As such, with both the A/T and the autopilot still engaged, the aircraft kept following the descend rate inputted by the pilot flying. Since the crew was already expecting a loss of altitude and airspeed for the interception of the glide slope from above, the crew failed to monitor their equipment fully and to update their understandings of the current operation mode of the A/T. Upon interception of the glide slope, the aircraft kept losing airspeed due to its idle-positioned throttle levers, which still remained undetected by the crew who was busy finalizing their checklists for landing.

The combination of the above mentioned occurrences contributed to the failure of the flight crew in stabilizing their approach at the time of reaching the altitude of 1,000 ft. As it was mentioned in Section 2.1, the general rule on an unstable approach would have required the crew to abort their approach and instead, perform a go-around. However, the crew of Flight TK1951 failed to do so, and continued their approach regardless of its non-stabilized nature. A continued and unnoticed loss of airspeed eventually led to the development of a stall. Once notified of the stall condition, through the stick shaker, the crew's initial attempts at a stall recovery was doomed to failure, since the crew was still not aware of the active mode of the A/T. The A/T revoked their attempts at increasing the generated thrust, and the aircraft kept losing airspeed and altitude. The point in time at which the captain became aware of the conditions was too

(a) The Tail Section (b) Front and Main Sections of the Fuselage

Figure 2.2: Aftermath of the crash of Flight TK1951 (Dutch Safety Board, 2010)

late, and any further attempts at recovering from the stall was unsuccessful.

The operation of Flight TK1951 during its final approach is considered as a specific case of a standard operation, in which a more specific and demanding event sequence was imposed on the flight crew.

2.3. OFFICIAL INVESTIGATION REPORT

The official investigatory body of the Netherlands aviation has provided a detailed description of their findings from investigating Flight TK1951 (Dutch Safety Board, 2010), and the identification of factors contributing to the final outcome of the operation. A summary of these findings is presented below. A more detailed overview can be found in Appendix A.

FAILURE OF RADIO ALTIMETER

The board concludes that the malfunctioning of the left radio altimeter caused a large reduction in airspeed, after the improper reading of the equipment led to a reduction of the total thrust to a minimal value too soon during the approach to runway 18R.

INSUFFICIENT MONITORING

The board also concludes that crew's failure in conducting a continuous and effective monitoring of airspeed prevented them from observing the improper functioning of the A/T. As such, they did not have the ability and proper knowledge of their systems to realize the development of the stall at an earlier time (Dutch Safety Board, 2010) (van Ruitenbeek, 2012).

SHORT LINE-UP

The board highlights that as a standard approach at Schiphol airport, flights can receive a short line up with the runway, as means of noise abatement techniques. However, it also highlights the fact that, following the specific sequence of events occurring on Flight TK1951, the short line up eventually contributed to the creation of the scenario for the automatic activation of the 'Retard Flare' mode of the A/T.

However, it should be realized that neither of the short line-up procedure and the early activation of the 'Retard Flare' mode of the A/T can be considered as critical and unsafe conditions (Dutch Safety Board, 2010). Given an informed and trained crew, the aircraft can still be flown safely, through incorporation of the necessary extra steps in re-configuring the aircraft accordingly.

HISTORY OF LRRA FAILURES

The DSB concludes that the Boeing 737-800 flown for Flight TK1951, with tail number TC-JGE, had experienced the problem with its malfunctioning LRRA-1 equipment on a number of its previous flights as well. In addition, it is also concluded that this issue was not specific to Turkish Airline's TC-JGE aircraft, but in fact was also reported by a number of Boeing 737-800's flown by other operators as well. However, none of these flights ended in any catastrophic condition similar to that of Flight TK1951, and the crews inside the cockpits managed to safely land their aircraft at all times.

3

ABM of Crew's Interaction with their Systems

Having outlined the operation resulting accident in Chapter 2, the existence and contributions of the numerous technical systems and human operators to the final outcome of the operation were outlined. This chapter applies the theory of Agent-Based Modeling (ABM) for the purpose of breaking down the operation into its constituting agents, such that a more detailed understanding of the interactions in between all relevant agents can be obtained. The primary focus remains on the modeling of crew's interactions with their systems, given the potential malfunctioning and unexpected system behaviors.

Appropriate modeling techniques are required to achieve a sufficient level of coverage of the interactions in between all relevant parties. Agent-Based Modeling is a promising theory, since it allows for a reconstruction of an operation using the elements that build up and contribute to the outcome of the operation. First, the ABM theory is introduced in Section 3.1, followed by an overview of the agents related to the operation considered, presented in Section 3.2. Next, the agents are introduced, and their characteristics and relations with regards to other agents are outlined. This is divided into two segments, namely the human and system agents, detailed in Sections 3.3 and 3.4, respectively. Having identified all agents, Section 3.5 will analyze the means available to the human agents to regularly update and maintain their situation awareness with regards to the status of the system agents.

3.1. Methodology

The operation of a commercial flight from point A to point B, such as Flight TK1951, can be modeled in various manners since it would include both social and technical aspects. The nature of the operation, being constructed by a combination of interactions between human beings, technical systems and external contributors such as weather effects, makes the analyses of such a socio-technical operation rather complex. For the purpose of presenting and analyzing these interactions and dependencies in the system, the ABM theory can be applied as a promising approach to simulate all interactions (Blom and Sharpanskykh, 2015). For a more detailed introduction to ABM, the reader can refer to Appendix C.

An Agent-Based model breaks the operation down into its constituting elements, labeled as Agents. An agent, while defined in various ways, can be described as anything that can be viewed as perceiving its environment through sensors, with the ability to act upon that environment (Macal and North, 2010). Agents can be in the form of human beings, (sub-)components of a larger system, or any other type of entity. An agent can be constructed by multiple sub-components, labeled as entities. However, regardless of the form the agent has, it must possess the ability to perceive its environment, and possess a Situation Awareness with respect to other agents and the environment these agents are situated at.

Endsley defines the Situation Awareness (SA) as "the perception of the elements in the environment... the comprehension of their meaning, and the projection of their status on the near future" (Endsley, 1995). The term SA thus refers to how informed and aware an agent is. The level of awareness can be with regards to own conditions, those of the other agents or of the surrounding environment in which all agents are situated. Although possession of a correct SA at any time t is crucial to ensure that an agent has a correct understanding of the entire environment around it, the process of continuously updating its SA is equally as important. The significance of an uptodate SA becomes more apparent when one comprehends the vast magnitude of factors that can possibly jeopardize the safety and outcome of the operation of a socio-technical system.

It should be realized that the possession of a SA is not only limited to human beings. In fact, depending on the design of technical systems, and the feedback loops implemented in between the sub-components, any technical agent will also have the availability to assess the information and the feedback received by the other systems in the environment. As such, the agent will be able to update own SA, and use it to re-configure itself as it is specified in its technical design.

In regards to the development of SA, an agent can follow three steps for the purpose of forming the required SA (Endsley, 1995). As the first step, Perception relates to perceiving by the agent of the state, attributes and dynamics of a subject agent. The second, Comprehension, relates to the integration of recognition and evaluation of the outcomes of Perception, in order to understand how it will impact the objectives of the individual. The third step, in which the highest level of SA is achieved, is a result of the outcomes of the two previous steps. Projection enables the agent to project the future actions of the subject agent and status of the environment. More information on the formation steps of SA can be found in Appendix C.

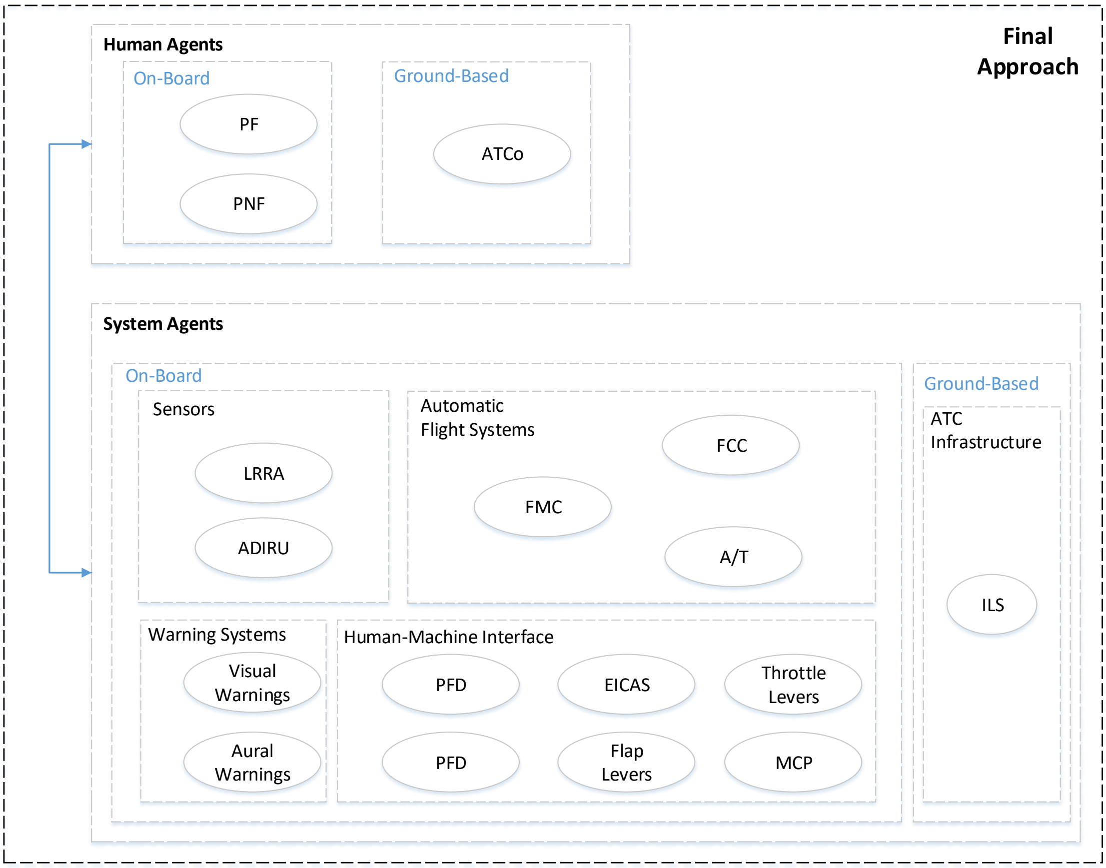

Figure 3.1: Overall Categorization of Agents relevant for the 'final approach' segment of a flight

3.2. RELEVANT AGENTS

In order to analyze any operation with the magnitude of a commercial flight, the agent population can easily expand to a significantly large scale. Although for a full and thorough understanding of the operation, all agents need to be established and analyzed, for the purpose of this report it would suffice to only consider the agents with a direct or indirect contribution to the events of the final approach of the flight. As such, various agents, although important for the safety and functionality of the overall flight, can be left out of the analysis. This would include both human agents, such as the cabin crew members, and various technical systems, such as the Traffic Alert Collision Avoidance System (TCAS).

To identify the relevant agents, and to ensure that the modeling would include all agents relevant to the occurrences of Flight TK1951, the detailed investigation report of Flight TK1951 (Dutch Safety Board, 2010) is used. In general, these agents can be identified under two categories, namely human and system agents. Figure 3.1 provides an overview of the corresponding categories and the relevant agents.

The human agents population consists of a conventional two-seated flight crew composition, in addition to the ATCo. On the other hand, the system agents population consists of two main systems, namely the on-board avionics and the ground-based ILS. These agent populations are next described in more details in their corresponding sections.

3.3. HUMAN AGENTS

As it was mentioned earlier, a conventional cockpit crew composition will be used for the simulations. As such, a conventional crew consisting of a Captain and a First-Officer will be used. The Captain, situated at the left seat of the cockpit, will be the head pilot of the flight. He will be the active PF, and will be in charge of controlling and flying the jet. On the other side of the cockpit, the First-Officer will be seated, who will be the PNF for the duration of the final approach. The PNF will be responsible for monitoring the equipment and cockpit displays, assisting the PF in adjusting flight parameters and configuring aircraft control surfaces if requested by PF, while maintaining a complete communication with ATCo.

It should be noted that Flight TK1951's crew composition included an additional crew member, namely the Safety Pilot, SP. The SP's tasks included a continuous monitoring of the flight parameters and the status of the flight in general, and to warn the PF in the event that the PF misses a critical occurrence. It can be concluded that in a conventional crew composition, these tasks are incorporated into the PNF's share of the task divisions.

In addition to PF and PNF, a third human agent is to be considered in the operation, namely the ATCo. While the responsibilities of an ATCo go beyond controlling the incoming traffic, with regards to the scope of this report, the ATCo's tasks are limited to monitoring and controlling the incoming traffic, specifically the aircraft of interest. During the approach of an aircraft, the ATCo will communicate and assign the crew with a STAR and remains the ground point of contact for the flight crew in the event of any abnormalities in the flight.

Remarks

An ATCo can use his or her displays at the ATC to monitor and assess the traffic around the airport. However, for ATCo to develop situation awareness of any abnormalities aboard a flight, this has to be manually communicated to the ATCo by the cockpit crew. If the ability of the crew in updating the situation awareness of the ATCo of any malfunctioning on-board the aircraft is jeopardized due to a busy workload or a serious malfunctioning, the ATCo will have no other real-time option of updating his or her SA. As such, the ATCo will be unable to provide any possible assistance to the crew. This highlights the role of the flight crew in providing an updated SA to the ATCo, when required.

The displays at the ATC provide the ATCo with the ability to perceive and observe relevant information regarding the current speed and heading, and the altitude assigned to the aircraft. As such, the ATCo can update own SA of the route flown by and the route ahead of the aircraft, without any dependencies on the communications with the flight crew. However, these SA updates are limited to the external characteristics of the flight. The investigation report also pointed out after the crash of Flight TK1951, that the ATCo failed to develop a correct SA of the route ahead of the aircraft. Due to the larger scale used on the ATC displays (Dutch Safety Board, 2010), the ATCo was unable to properly project the future actions required by the flight crew regarding the interception of the glide slope. As such, the ATCo failed to obtain a full and correct SA with respect to where the aircraft would intercept the localizer and the glide slope signals. The insufficient SA of ATCo with respect to the projected route of the flight meant no data was communicated to the flight crew. As such, they had to rely on their equipment and cockpit screens to manually observe the route changes and update their own SA's with respect to the required reconfiguration of their aircraft.

3.4. SYSTEM AGENTS

Similar to the division of the human agents, Figure 3.1 establishes two overall categories of systems, namely the on-board and ground-based avionics. While for the ground-based avionics, only the ATC infrastructure is of interest, the on-board avionics are further divided into four subcategories, which will next be described below. In order to maintain a level understanding of potential interactions, a Boeing 737-800 aircraft is used for modeling purposes throughout the report.

3.4.1. SENSORS

In regards to the sensors applicable for an approach flight, two system agents can be introduced.

LOW RANGE RADIO ALTIMETER

As it was described in Chapter 2, the LRRA-1 on-board Flight TK1951 experienced a malfunctioning throughout the final approach, and thus provided wrong data to the crew and to the other system components the LRRA-1 interacts with. In total, two LRRA's are present in the cockpit, each providing the measurement of the radio altitude to their corresponding side of the avionics in the cockpit. The avionics components receiving the output of the LRRA's can be categorized in three parts. First, one can mention the display units which will present the outputs to the flight crew. The second category contains warning systems, including the warning for the landing gear configuration. The third refers to the category of automatic flight related systems, including the A/T, the Flight Management Computer (FMC) and the Flight Control Computers (FCC) (Boeing, 2009), all to be detailed later. This highlights the importance of this equipment, as it interacts with crucial system agents of the avionics.

The output of the LRRA consists of the specific measurement of the RA, along with an indication of the mode at which the output was computed. For this, the mode can be characterized as one of the following (Dutch Safety Board, 2010):

- **Normal**: no errors have been detected, and the data is considered usable.
- **Fail Warn**: the LRRA computer has marked the signal as unreliable due to a failure in LRRA. The output RA is thus not meant for usage by any system.
- **Non-Computed Data, NCD**: LRRA is operating correctly, however the signal received is too weak and the output RA is thus not used by any system.

In order for the LRRA computer to determine the mode in which the results are computed, it uses the following schema (van Ettinger, 2013):

Table 3.1: Requirements for the determination of a RA output (van Ettinger, 2013)

Signal Strength	**RA Range** [ft]	**Erroneous Reading**	**LRRA Signal Mode**	**Valid Signal?**
> Threshold	-20 to 2,500 ft	No	NORMAL	Yes
		Yes	FAIL WARN	No
	-20 to 2,500 ft	No	FAIL WARN	No
		Yes	FAIL WARN	No
< Threshold			NCD	No

As it can be seen in Table 3.1, the only scenario in which the RA signal is considered as 'valid', is when the measurement is within the range of -20 to 2,500 ft, with a signal strength above the threshold and with no erroneous reading detected.

Remarks

It has been tested and proved that the output RA may be sent to the corresponding systems irrespective of the output mode at which the signal was computed (van Ettinger, 2013). In fact, the A/T can still use the output RA as valid input, while the mode was computed as "NCD" by the LRRA computer (Dutch Safety Board, 2010). It appears as the detection of an erroneous mode of the output RA is left to the receivers of this signal, including the A/T.

AIR DATA INERTIAL REFERENCE UNIT

An Air Data Inertial Reference Unit (ADIRU) consists of two main components, an Air Data Computer (ADC) and an Inertial Reference Unit (IRU). Relevant to the analysis is the ADC, which uses air data to compute the aircraft's airspeed, Mach number and barometric altitude. The digital data collected, along with a digitized version of the analog air data collected are next fed into the corresponding system agents. The system components to use the ADIRU outputs include flight displays, flight management computers, engine controls, and basically any other flight system which requires the input of inertial and air data for executing and computing its outcomes (Fyfe, 2013).

Remarks

Although proper functionality of an ADIRU is essential for calculation of correct flight data such as airspeed, the flight crew's knowledge about the design and working principle of an ADIRU is considered irrelevant for the purpose of this report. However, the element that remains crucial for this modeling is the crew's ability in having direct overview of the outcome of this measurement component. Since the outcome of an ADIRU can be accessible through the interfaces available to the crew in the cockpit, this is considered sufficient for ensuring that the crew can at all times have access to the current flight data if required.

3.4.2. AUTOMATIC FLIGHT DIRECTOR SYSTEM

As outlined in the description of the crash in Chapter 2, Flight TK1951 experienced a major deficiency of the cockpit crew's SA regarding the possible interactions between the malfunctioning LRRA-1 and the components of the Automatic Flight Director System (AFDS). This highlights the necessity to fully understand how LRRA interacts with the components of AFDS, and how the computed RA is used by the AFDS agents. The AFDS is divided into three main components, to be considered as agents:

FLIGHT MANAGEMENT COMPUTER

The Flight Management Computer (FMC) acts as the brain of the AFDS. It receives the measurement over the current status of the aircraft from the measurement sensors, and combines it with data from the in-built storage unit and the crew's inputs to the cockpit interactive displays. It will then compute the data feedback required by AFDS components to achieve the required reconfiguration of aircraft.

The commands generated by the FMC are based on the differences between the current flight status and the flight parameters selected by the crew or the desired flight path (Spitzer, 2001). In regards to the current flight status, the ADIRU's and the LRRA's are responsible for providing the flight parameters. As such, it is clear that the data provided by the measurement systems are essential for a proper functioning of the AFDS components.

The commands sent by the FMC to the AFDS components will include the required parameters of airspeed, altitude and heading, along with engine power settings to be obtained at the appropriate flight phases (Borst and Mulder, 2015-2016a).

FLIGHT CONTROL COMPUTER

A Flight Control Computer (FCC) is responsible for translating the FMC's commands into pitch, roll and yaw inputs to be executed in order to achieve the required reconfiguration of airspeed and flight path (Borst and Mulder, 2015-2016a). With two FCC's installed, each feeds the commands to their own side of the cockpit avionics. The FCC's construct two main components of the AFDS, namely the AutoPilot (A/P) and the Flight Director (F/D). An A/P is responsible for reconfiguration of the aircraft such that it automatically follows the desired flight plan according to the flight parameters computed by the FMC and inputted by the crew. A F/D, however, provides the crew with a representation of the required level of pitch and roll inputs to achieve the desired outcome. As such, the F/D function does not provide any automatic flight, but shows the crew what deviations are required.

Remarks

For the event of Flight TK1951, the ATCo failed to observe and communicate to the crew the requirement for the flight crew to intercept the glide slope from above, due to the active settings he or she had on the ATC displays at the time of operation. However, it is believed by the DSB that the captain was able to observe the guidance shown by the F/D command bars on the PF's PFD, and as such, proceeded to execute the necessary steps to make sure the aircraft would properly descend towards the glide slope.

The guidance shown by the F/D command bars will be implemented as means of SA updating. Given the crew's availability to observe the commands, the command bars will be observed, comprehended and the crew's SA can be updated regarding the next required set of actions. It should be kept in mind that, as mentioned earlier, no SA updating through communication with the ATCo is available to the flight crew, due to ATCo's failure in updating own SA in a timely manner.

One final remark concerning the FCC's is regarding the modes at which FCC's can operate. An FCC can operate under various modes depending on the phase of the flight and the activated flight systems. Although this is essential for making certain functions of the AFDS system possible, the active mode can, in combination with other settings, lead to significant possibly unwanted changes in the state of some other components. Essential for modeling purposes of this report, this will be further outlined next under the description of the Autothrottle.

AUTOTHROTTLE

The Autothrottle is a single computer system, with the purpose of providing indirect control of the thrust output of the engines. When engaged, an A/T will automatically operate the servos to re-position the throttle levers, which will in turn re-adjust the level of thrust generated by the engines. The throttle levers are positioned in between the two flight crew members, and can also be re-positioned manually by either of the cockpit members. However, for a manual operation of the throttle levers, the A/T must be disengaged; otherwise, the crew's inputs will be overcome by the A/T inputs (Dutch Safety Board, 2010).

Remarks

Two remarks will be made regarding the functionality of the A/T. The first is related to the interactions between the two LRRA's, and the A/P and A/T systems installed aboard the aircraft. The A/P, as a sub-component of the FCC's, and the A/T both receive inputs from the radio altimeters, regarding the altitude the aircraft is flying at. This can also be seen in the illustration shown in Figure 3.2.

However, the point of interest is with regards to how the output of the LRRA's are used by these two components of the AFDS. The left LRRA, located on the cockpit side of the PF and responsible for feeding the left side of the avionics, provides the RA input for the left A/P. In addition, under normal operation circumstances, the left LRRA also provides the RA input for the A/T computer. The right LRRA provides the same input type for the right A/P. The left LRRA is thus the primary source of RA inputs for the A/T. In fact, only in the event that the generated signal by the left LRRA is not labeled as 'Normal', will the A/T change its RA input source to the right LRRA (Dutch Safety Board, 2010). This is also illustrated in Figure 3.2, in which an active secondary signal indicates the scenario in which the primary signal has not been marked as 'Normal'. Upon failure of both LRRA's to provide RA inputs correctly labeled as 'Normal', the A/T will disregard all RA inputs and will automatically disengage (Dutch Safety Board, 2010).

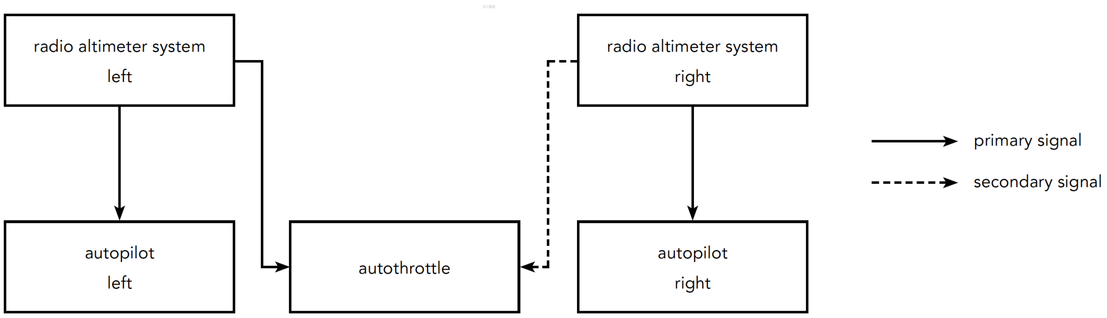

Figure 3.2: Feedback of Ra input from the LRRA's into the A/P's and A/T (Dutch Safety Board, 2010)

While a pilot will have no direct indications of the mode at which the RA output is computed, the PF or the PNF can update their SA regarding a disconnection of the A/T, or that of the A/P should it occur, through observation of their cockpit instruments and displays, and the generated warning sounds dedicated for such occurrences. As such, it becomes clear that although direct references to certain malfunctioning aboard the flight might not be visible to the crew, such as that of the LRRA-1, maintaining a continuous and proper observations of their instruments can always assure an updated SA of the crew regarding the their avionics systems, or the aircraft status in general.

The second remark concerns the working principles of the A/T. For this purpose, the possible thrust modes at which the A/T may function throughout the flight will be discussed, along with the relevant pitch modes of the FCC. Both the A/P and the A/T will be functioning under different modes throughout the flight, based on the flight phase and the required functionality of the AFDS to achieve the desired changes to or to maintain the current flight status. While an A/P will include modes applicable to both roll and pitch commands, only the pitch modes will be of interest to this modeling.

An A/T can automatically activate or deactivate its 'Retard Flare' mode, depending on whether if certain requirements have been met or not. This section will outline these requirements, and the corresponding modes of the A/T and the A/P. The following list defines the requirements for an automatic activation of the 'Retard Flare' mode:

1. The RA input reads a maximum value of 27 ft.

2. Flaps set at a minimum of 12.5 $degree$.

3. A thrust mode of the A/T at which airspeed is being controlled.

4. A pitch mode of the FCC at which the altitude is not controlled.

A RA input of an altitude of less than or equal to 27 ft is thus required. For this, the RA signal received from the corresponding LRRA should have read as 'Normal', for the A/T to use it. Next, it should be realized that all these conditions must be met simultaneously, for the 'Retard Flare' mode to be activated. Thus, in addition to an RA of

Table 3.2: Thrust and Pitch modes of the A/T and the A/P, respectively

Thrust Mode	Controls Airspeed?	Pitch Mode	Controls Altitude?
ARM	-	V/S	-
N1	-	ALT ACQ	✓
GA	-	ALT HOLD	✓
FMC SPD	✓	VNAV SPD	-
MCP SPD	✓	VNAV PTH	✓
THR HLD	-	MCP SPD	-
Retard	-	G/S	✓
Retard Flare	-	Flare	✓

maximum 27 ft and flaps of minimum 12.5 $degree$, certain modes of the A/T and the A/P are required as well.

For the A/T, a thrust mode that provides means to control the airspeed is required. Table 3.2 provides the different modes at which an A/T can be operating. As it can be seen in this table, the airspeed is only controlled under the 'FMC SPD' and the 'MCP SPD' modes. The former controls the thrust to maintain the airspeed required by the FMC in an automatic flight (Boeing, 2008), while the latter bases its thrust commands on PF's direct inputs (Boeing, 2008).

On the other hand, for the A/P, a pitch mode of the FCC that does not control the flight altitude is required. A pitch mode incorporates the commands of FCCs into the FCC components, namely the F/D's and the A/P's. As it can be seen in Table 3.2, three modes come into play with no control over the altitude (Boeing, 2008), the 'V/S', 'VNAV SPD' and 'MCP SPD' modes. The first mode, namely the 'V/S' will be of interest for further analysis in this report, in which the vertical speed is held using FCC pitch commands through the A/P or the F/D.

The cockpit crew can update their SA regarding the active modes of A/T or the A/P, through manual observation of their cockpit displays and the remarks given on these displays. Upon activation of the 'Retard Flare' mode, an indication of this mode will also be visible to each member of the flight crew on their corresponding PFD's. The information regarding the active or armed flight modes can be found on the top row of their PFD's. An illustration of the flight mode annunciations shown to the crew of Flight TK1951, throughout their final approach and descend, is given in Figure 3.3.
As it can be seen in Figure 3.3, the automatic activation of the 'Retard Flare' mode occurs after the aircraft starts its rapid descend towards intercepting the glide slope. Presented at point three on the figure, it can be seen that the corresponding modes of the A/T and the A/P at this time are the 'MCP SPD' 'V/S' modes, respectively. This is while, having had a fully functioning LRRA-1, a normal flight condition would have not had led to an automatic activation of the 'Retard Flare' mode.

An A/T computer can also automatically deactivate its 'Retard Flare' mode, given one of the conditions listed below are met (Dutch Safety Board, 2010):

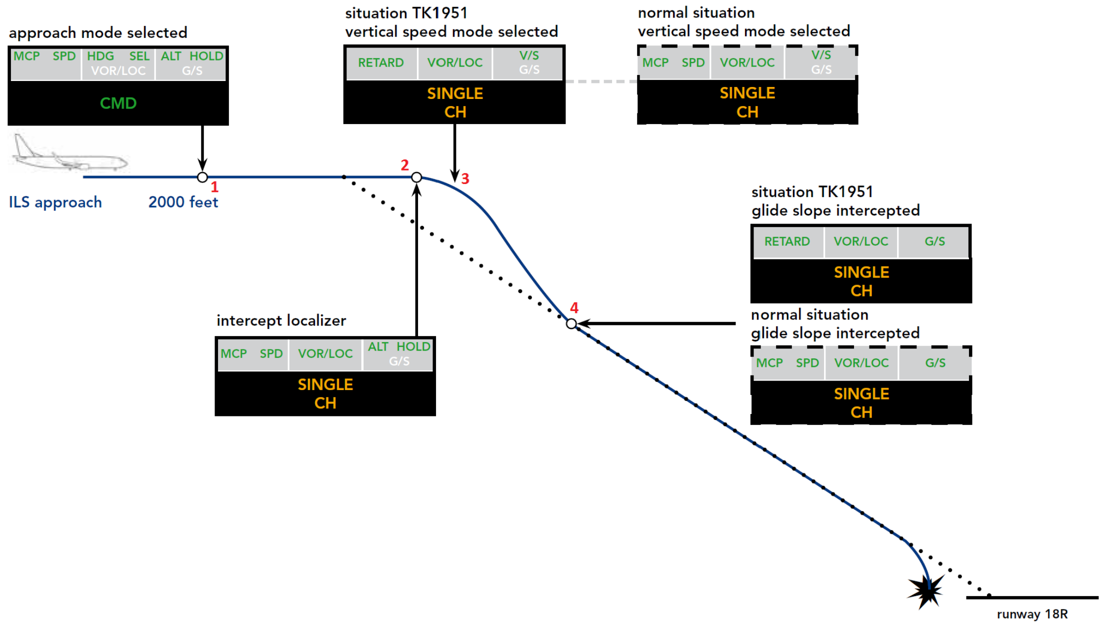

Figure 3.3: Illustration of flight mode annunciations, on Flight TK1951 (Dutch Safety Board, 2010)

1. A/T is disengaged.
2. A Go-Around procedure is initiated.
3. An invalid or out of range RA input.

For the case of Flight TK1951, given the unwanted early activation of the 'Retard Flare' mode due to the faulty RA inputs, the crew failed to correct for the A/T mode by executing any of the first two options listed above. An incorrect assessment of the A/T regarding the computation mode of the RA inputs also prevented the A/T computer from automatically switching to the LRRA-2 RA data or disengaging itself as a result.

3.4.3. HUMAN-MACHINE INTERFACE

A set of interfaces present in the cockpit provide a continuous and live link between the avionics system agents and the flight crew. These are named as the Human Machine Interface (HMI) of the cockpit. With the various avionics and human agents described earlier in this chapter, the HMI provides a medium for the purpose of exchanging information and mutual communication between electro-mechanical agents and the human agents operating these systems. The HMI can be broken into vast numbers of components, of which the components considered relevant to the flight scenario of Flight TK1951 are mentioned here.

PRIMARY FLIGHT DISPLAY

The Primary Flight Display provides the most relevant flight status data on a single but cleanly formatted display. A PFD displays information of almost all flight data parameters, including various critical information such as airspeed, altitude, heading and vertical speed. It is the primary source of information for the flight crew to update their SA regarding the current and future status of the flight. In addition, a PFD also hosts the guidance given by the F/D command bars and visual warnings regarding deficiencies in flight parameters such as airspeed and altitude. The crew must continuously monitor, pick up and reason the information available on the PFD's in order to achieve an accurate SA and uptodate projection of the future status of the flight. An example of the PFD, representing the various data types illustrated, is shown below in Figure 3.4.

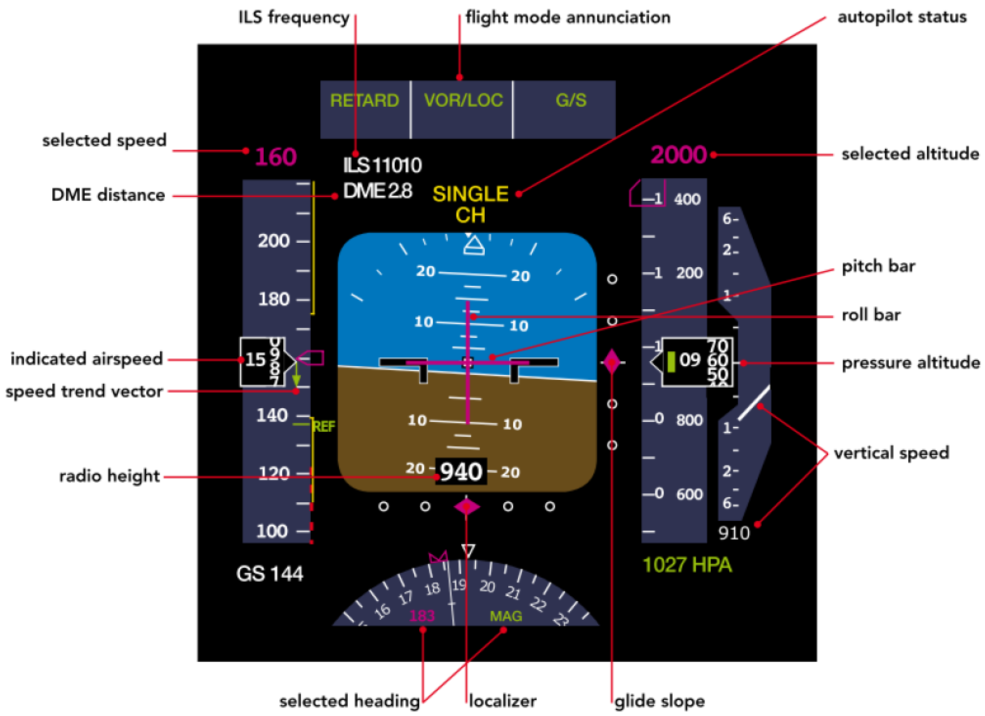

Figure 3.4: Illustration of Boeing 737-800's Primary Flight Display (Borst and Mulder, 2015-2016a)

Remarks

Although a PFD provides the crew with the information needed to assess the flight, the crew still remain arguably prone to failure in properly detecting essential information or warnings at all times. A warning backed up with an aural indication is more likely to be noticed than an illustration drawn on a screen, which can only be picked up by the pilot if he or she takes an initiative in examining and thus observing the data presented. Two factors may be playing a role here. An increased task load or stress level can cause a decrease in the awareness level of the crew, or their ability to focus on continuously monitoring their PFD's. In addition, human beings have been described in various studies as being subjected to performance deterioration after long shifts of continuous monitoring (Davies and Parasuraman, 1982) (White, 2003), and as such may start missing the information presented to them as the monitoring period extends. This can be partially backed up by the actual occurrence of Flight TK1951, through which the safety pilot present in the cockpit failed to warn the PF in time regarding the loss of the airspeed.

ENGINE INDICATION AND CREW ALERT SYSTEM (EICAS)

Engine Indication and Crew Alert System (EICAS) helps in keeping the crew informed of the most important parameters of their engines, and informing them if certain parameters of the engines are no longer according to the range in which they should be operating, or the value expected by the flight phase.

Remarks
The same remark given for the PFD is considered applicable to the EICAS, in terms of possible failure of the flight crew in detecting any indication of malfunctioning on the EICAS properly and in a timely manner. However, since the act of monitoring for the essential flight parameters is included when considering the interaction between human agents and the PFD, addition of EICAS to the list of agents is no longer deemed necessary.

CONTROL COLUMNS AND FLAP LEVERS
Control columns, located in front of the cockpit, provide the primary means of direct steering of the aircraft to the flight crew. On the other hand, flap levers allow the crew to adjust their flaps settings, according to the required flight phase and the airspeed the aircraft is flying at. It is considered as common flight exercise for the PNF to be in charge of adjusting the flap settings. If changes are required, the PF will be asking the PNF to move the flap levers and change the flaps settings accordingly. Upon receiving the command from the PF, the PNF performs the task, checks for proper completion of the task and reports back to the PF.

Remarks
The flap levers, in addition to providing the mechanical adjustments to the wing surface for flying at the required airspeed, also play a significant role in how the 'Retard Flare' mode of the A/T is activated, as it was discussed earlier. However, considering that the control columns and the flap levers are fixed at the position determined by the flight crew, and that no other automatic influence of the flight is available by these components, they shall not be considered as individual agents to this report. An uptodate SA of the crew with regards to the position of the flap levers still remains a requirement throughout the flight.

THROTTLE LEVERS
Adjustable both manually by the cockpit crew and automatically through the servos controlled by the A/T computer, the position of the throttle levers determines the thrust generated by the engines. However, for crew's manual inputs to alter the position of the throttle levers, the A/T must have been disengaged.

Remarks
Although essential for the engines to determine the level of thrust to be generated required for staying in the air, throttle levers are not considered as agents applicable to this report. The reasoning behind this decision is similar to that of the control columns and the flap levers, considering the inability of the throttle levers to automatically alter or influence other agents' behaviors.

It is, however, essential for the safety of the operation for the crew to maintain an uptodate overview of the location at which the throttles are located. This requirement applies to controllers of other mechanical equipment as well, such as the control columns and the flaps. An incomplete monitoring and realization of the 'idle' position of the throttles proved catastrophic for Flight TK1951, as the crew failed to realize that the aircraft engines were no longer producing the needed level of thrust.

MODE CONTROL PANEL

The MCP is the AFDS input interface available to the flight crew to input their commands for the A/P and other related components of the AFDS. The control inputs applicable to the modeling of this report are related to the changes in heading, altitude and airspeed.

Remarks

What should be realized is that the MCP is the interface between the flight crew and the components of the AFDS. As such, for the inputs of the crew into the MCP to have any influence on the overall performance of the aircraft, the relative components of the AFDS must be engaged and active. Otherwise, the inputs will not be effective. The crew can, at all times, assess the status of their AFDS components through a combined monitoring of the PFD and the MCP.

With the AFDS components of A/T and A/P engaged, the MCP remains an active and influencing piece of equipment, controlling the flight through the settings set on this panel. As such, the MCP is considered as a contributing agent, whose continuous updating and monitoring by the flight crew will be essential for the development of the flight scenario.

3.4.4. WARNING SYSTEMS

As it was mentioned earlier, the performance of a human agent may easily be jeopardized by the complexity of the operation or an increased work load, lowering the probability that the human would detect a visual warning. As such, the aural warnings would have the benefit that the noise generated is more likely to be detected by the crew and receive their attention. A situation, however, could also occur in which an aural warning is detected by the crew, but due to the complexity of the operation or an enormous task load at the time, the crew members forget to act upon the warning after performing their instant task at the time.

This report will only focus on a limited sources of warnings generated in the cockpit. These include the landing gear configuration warning, Stall Warning System (SWS), Mach/Airspeed Warning System (MAWS), visual warnings presented on the PFD regarding the loss of altitude or airspeed below the minimum operational limits, and the aural warnings regarding disconnections of the A/T and the A/P.

Remarks

It should be realized that the modeling of the warning systems will not be within the scope of this research. However, the detection of the automated warnings by the flight crew will be used for two purposes. First, having detected the warning induces an increased number of tasks to be performed by the pilot. In addition to the detection of the warning, the pilot will have to comprehend the new information and use it to assess the current status of the flight. Only then, will the pilot be able to make a projection of future conflicts or the state of the relevant component.

Secondly, variations in the performance rate of the flight crew in responding to the generated warnings can be used to recreate the reference flight scenario under different circumstances. This can indeed have significant consequences on the development of the event sequence, and at certain conditions, can result in hazardous situations. An example, that also occurred on Flight TK1951, would be related to the failure of the flight crew in detecting the presence of mismatching LRRA outputs. If not perceived by the crew, the crew loses the ability to comprehend the meaning behind such differences and the potential causes behind the occurrence. No communication shall take place in between the two crew members to update their SA of the development of a potentially hazardous situation, and no projection will be made with regards to the future state of the LRRA's and the other system agents to be possibly affected by the LRRAs' malfunctioning.

A second example would be the event in which the visual warning signs illustrated around the airspeed indicators on both PFD's are not detected by the pilots. As such, the crew will not be able to anticipate the loss of airspeed, which can in the worst case, lead to a development of a stall condition.

3.4.5. ATC SYSTEM

The second category of systems, located on the ground, is the ATC infrastructure and all components related to it. For the purpose of this report, ATC can be broken down into ILS infrastructure, arrival routes and the associated guidelines and noise abatement techniques to be communicated to the flight crew by the ATCo. The flight crew will be in contact throughout the approach with the controller, from whom they shall receive instructions on how to approach and land on the runway. As such, the primary point of SA update for the crew regarding the ATC procedure and availability of ILS components.

While an ATCo issues the overall guidance and instructions on how to approach the airport, and although the aircraft is fully capable of automatically capturing and following the ILS signals, the crew is still responsible for a continuous monitoring of their equipment at all times. Various tasks remain to be performed by the flight crew, including the configuration of the on-board ILS avionics, configuration of flaps and landing gears, and the assessment of the state of the approach and execution of a go-around, if necessary.

Remarks
The performance of the ATC infrastructure and the ATCo will not be further studied. As such, an assumption will be made, assuming full functionality of the ATC at the moment of the final approach, with the controller issuing instructions fully and at the right time. This will assist in keeping the focus on the performance of the flight crew, and their ability in perceiving, understanding and implementing the instructions to turn in the aircraft for the final line-up with the runway.

3.5. AWARENESS OF HUMAN AGENTS ABOUT OTHER AGENTS

The previous section helped in identifying the list of system agents relevant for the modeling of this report. Next, the means available for the two cockpit crew members for updating their SA's of these systems are discussed. Through observation, communication, and reasoning, each pilot will be tasked with constantly upgrading own SA with regards to the states of the system agents, such that the crew can stay informed and in control of the flight throughout the final approach.

Table 3.3 discusses the interactions of the flight crew with the other agents, for the purpose of updating their SA with regards to each of these agents. Compared to the agents breakdown provided earlier in Figure 3.1, Table 3.3 does not further study the systems of ADIRU, EICAS, FMC, and the Flap Levers. From the two components of the FCC, only the A/P is considered further, dropping the F/D out of the SA-update matrix. And, considering the ground-based agents, only ATCo is further considered for the purpose of assessing the sufficiency of air-ground information exchange.

Table 3.3: Discussion of means available to flight crew to update their SA about other agents

	Observation	**Communication**	**Reasoning**
LRRA	Each crew member is only supported with a final presentation of the outcome of own LRRA. No insight is available to the crew regarding the functionality of the LRRA, nor regarding the determination of the signal mode.	At periods of higher work intensity, or in the event the crew has to deal with an immediate hazardous situation, the malfunctioning of own LRRA needs to be communicated by the corresponding pilot.	If faults are not observed, no reasoning can be done towards possible causes and consequences.

Continued on next page

Continuation of Table 3.3

	Observation	**Communication**	**Reasoning**
	As such, the crew can only update their SA through observation of the values presented to them on their PFD screens.	In the event the differences in LRRA outputs are not observed, crew will not be warned and as such, no communication shall take place in order to comprehend and investigate potential causes behind such differences, nor will the crew make a projection of future influences of such RA differences on other avionics.	
A/P	The mode under which the A/P is functioning can be perceived by the crew through checking their PFD's. Failure or disengaging of A/P will also be aurally warned to the crew.	No external communication will be provided to the crew concerning functioning state of their A/P's.	Although the crew can successfully observe an active pitch mode of V/S, VNAV SPD or MCP SPD, there is no means available to assist them in forecasting an automatic activation of the 'Retard Flare' mode of the A/T. Crew's SA of the active A/T mode can only be updated through manual inspection of PFD.

Continued on next page

Continuation of Table 3.3

	Observation	Communication	Reasoning
A/T	The mode under which the A/T is functioning can be perceived by the crew through inspecting their PFD's. Failure of disengaging of A/T will be aurally warned to the crew. A feedback of a faulty RA into the A/T is not to be observable by the crew. The crew must observe the faulty RA or the mismatching in between the two RA's through manual inspections of their PFD's.	No external communication will be provided to the crew concerning functioning state of their A/T. It is up to the crew members to raise awareness of any abnormalities regarding the A/T and to inform the other crew member.	Only upon detection of an early activation of 'Retard Flare' mode, will the crew be able to assess and reason for a potential malfunctioning A/T. No direct warning is available to the crew to help them in projecting the potential consequences of an erroneous RA output on their A/T system.
PFD	In order to use the data, guidance and alerts available on the PFD, the pilot must manually monitor and read off the data from the equipment. In other words, pilot's failure in properly monitoring the PFD equals failure in updating own SA, with potentially significant consequences on safety.	The PNF is responsible for a continuous monitoring of the flight data presented on his or her PFD, and communicating any abnormalities to the PF at all times. This will ensure that while the PF is occupied with flying the jet, the PNF can raise awareness and update PF's SA of any malfunctioning.	The PF can only reason and project for potential consequences of a flight deficiency, given the PF has personally detected the deficiency from own PFD, or been informed by the PNF.

Continued on next page

Continuation of Table 3.3

	Observation	Communication	Reasoning
Throttle Levers	The crew will have to manually monitor the location of the throttle levers to update their SA's. Located in between the crew members, any of the two should have easy access to the throttles. There are no means available to the crew for updating their SA's of the condition in which all requirements for an automatic push back of the throttles into an idle position are met. Manual inspection of active mode of the A/T and position of the throttle levers remain as crew's only options for updating their SA's.	No external communication is available for means of updating the SA.	Observation of an early idled throttle levers can warn the crew and help them in communicating the possible causes and as such, leading them to realizing the erroneous active mode of the A/T. However, if not observed, no communication and reasoning shall take place. As such, the crew will not have the opportunity to react to the conflict.
MCP	For a complete SA, crew must combine their observations of MCP and PFD. Observation of the settings selected on MCP is not sufficient for ensuring a correct SA of the functionality of AFDS components. For instance, MCP might indicate an 'engaged' and 'functioning' A/T, while the PFD indicates an abnormal active mode.	Communication between the crew members remains a crucial method of achieving an even SA in the cockpit.	The crew can only realize that A/T is not controlling the airspeed, if they correctly observe the 'Retard Flare' mode of A/T on PFD. Only the realization of the inappropriate mode of the A/T can help the crew reason for a malfunctioning of the A/T or of a related component.

Continued on next page

Continuation of Table 3.3

	Observation	**Communication**	**Reasoning**
Visual Warnings	Visual warnings require attention of the crew in order to be fully comprehended. Compared to aural warnings, visual warnings are in general subjected to a higher probability of remaining undetected by the crew.	Communication of the detected warning will help in yielding an even SA in the cockpit about the potential hazardous situation. This can be particularly useful if either of the crew members are fully occupied with other primary tasks.	Failure of crew in observation or communication of the findings prevents them from making a proper conflict assessment, and as such, no complete projection of potential consequences on the remainder of cockpit equipment shall be achieved.
Aural Warnings	Benefiting from the external aural sound generated, the crew is more likely to pick up on the warning, compared to a visual warning. However, this does not guarantee that the crew will act upon the warning. This depends on the magnitude of current task load and availability of the crew, and the complexity of the flight condition.	Communication of the detected warning will help in yielding an even SA in the cockpit about the potential hazardous situation. This can be particularly useful if either of the crew members are fully occupied with other primary tasks.	Failure of crew in observation or communication of the findings prevents them from making a proper conflict assessment, and as such, no complete projection of potential consequences on the remainder of cockpit equipment shall be achieved.

Continued on next page

Continuation of Table 3.3

	Observation	**Communication**	**Reasoning**
ATCo	An ATCo can monitor the overall status of the flight through the displays available at the ATC. Parameters such as airspeed, altitude and heading of the flight will be visible to ATCo. However, depending on factors such as current ATC display settings, ATCo's workload, ATC environment, or potential ATC limitations, the ATCo's performance might be jeopardized.	Upon failure of the flight crew in perceiving and responding to ATCo's instructions, ATCo will contact the crew again and re-communicate the instructions to the crew. It is a standard routine for ATCo, resulting in crew's read-back or request for alternatives.	Upon a non-stabilized approach, the crew will have to assess the situation and decide if there will be enough time to complete all tasks prior to the final descent and landing. Otherwise, a go-around will have to be issued. The decision on a go-around will have to be communicated to the ATCo.
			Concluded

Having established the overall boundaries of tasks to be completed by the flight crew, and the means available to the crew to conduct these, the crew's performance rates under different flight conditions will be analyzed next.

4

Human Performance Modeling

Chapter 3 outlined the existence of vast numbers of possible interactions in between the crew members, and in between the crew members and the numerous cockpit systems. The significant contributions of human agents to such a complex socio-technical system helps establish the importance of the human-performance factor even further.

To do so, this chapter aims at providing a break down of human agents' responsibilities and interactions with their surroundings and the system agents identified in Chapter 3. Generic and specific responsibilities of each member of the cockpit crew throughout the final approach are identified and analyzed, with regards to the human cognitive and performance abilities.

Section 4.1 first outlines the approach of Contextual Control theory, describing the different modes at which the human operators may be operating, and the corresponding levels of performance deterioration. Next, Section 4.2 introduces and executes the steps in breaking down the crew's tasks into two specific clusters of tasks applicable to the PF and PNF, respectively. This is coupled with the application of the control modes of the Contextual Control theory, describing how a deterioration of cognitive control mode can negatively affect cockpit crew's performance. A discussion on the findings is next provided in Section 4.3.

4.1. Contextual Control Theory

Various numbers of studies have focused on analyzing human performance in complex situations. Among these, a number of studies with the main focus on human performance in the context of Air Transportation (Blom et al., 2001) (NLR, 2009) have been consulted for this report. The purpose of the modeling of human performance at this chapter is to help demonstrate how significantly the human's performance would change given the deterioration in ability to focus, make decisions or receive information from the surrounding equipment.

As it was described in Chapter 3, although the on-board avionics are meant to provide the crew with the necessary tools to obtain full control and SA of the flight status at all times, sufficient updating of the crew's SA can not always be guaranteed. To better understand why such a statement holds true, one should have a detailed model representing the possible variations of the cognitive viewpoint possessed by the human operator throughout the operation. For this purpose, the performance model of Hollnagel (Hollnagel, 1993) is used. The performance of a human operator is decomposed into four specific levels of performance modes, each reflecting distinctive ability in planning and executing simultaneous tasks, with variable event horizons (Blom et al., 2001). As such, depending on the control mode at which the operator will be acting, different operation outcomes are possible.

4.1.1. CONTROL MODES

Four characteristic modes are considered in Hollnagel's Contextual Control theory, providing four levels at which the regularity and success rate of a human operator's performance can be categorized. The Control Modes are described below (Hollnagel, 1993) (Blom et al., 2001) (Jaberi, 2017), in the order of improving performance and increasing SA:

1. **Scrambled** mode:
   Corresponds to the situation in which the choice of the next action is random or irrational. Represents a deficiency in SA, and is an indication of zero control.

2. **Opportunistic** mode:
   Relates to the situation in which the choice of the next action is determined only through crew's current understanding of the conflict importance. As such, the next course of action is limited to the first possible solution thought of by the operator. Limited SA and planning emerges, following the limitations in time or understanding conflict clarity.

3. **Tactical** mode:
   In a tactical mode, having realized the conflict, the operator is expected to use a known procedure or follow the steps dedicated by the regulations. However, although more time is available to the operator, compared to the previous two modes, the planning outcome will still be of somewhat limited scope.

4. **Strategic** mode:
   Considered as the highest performance mode, the operator acting in a strategic control mode will benefit from a wider time horizon available. The choice of the next action is supported by the opportunity to look ahead and plan in advance. In addition, the operator will have the opportunity to spend time for assessing tasks ignored in the past. This action, however, can not be guaranteed.

As it can be understood from the control modes described above, an operator's control over the situation is represented as a continuum, with very little to no control at a scrambled mode, while on the other hand, a strategic mode symbolizes a high degree of control and ability to execute the planned decisions. It should be noted that no single control mode can represent a most complete performance across all time limits (Feigh et al., 2006). The classification provided by Hollnagel, however, helps homogenize the modeling of human performance throughout various degrees of comfort, availability of time, and degree of control.

4.2. BREAKDOWN OF CREW'S TASKS

For the decomposition of the flight crew's tasks during the final approach of the flight, the approach of a similar paper on human cognition performance model in the context of air transportation (Blom et al., 2001) is used. The breakdown of tasks is conducted in two dimensions. First, a generic dimension is studied, in which cognitive tasks at a general level with respect to the overall boundaries of the operation are defined. As such, no attention is paid to the specific operational concept of the operation under study. This will help in creating an operation-independent decomposition of crew's tasks.

The latter is a scenario-specific dimension, which concerns all tasks and responsibilities expected of the flight crew with regards to operation scenario. Having established the general and specific tasks, one will next be able to combine the two dimensions to allow for an overall integration of the tasks, and a specific representation of the individual tasks to be conducted. These can next be specified to the PF, PNF, or to both.

A complete list of steps in modeling the performance of a cockpit human agent (Blom et al., 2001) is given in Table 4.1. Each step and the results will be detailed next, in the order given in Table 4.1.

Table 4.1: Steps in modeling performance of cockpit human agents (Blom et al., 2001)

Step	Description
1	Identification of Generic Tasks
2	Identification of Operation-Specific Tasks
3	Integration of Generic and Specific Tasks
4	Allocation of Tasks to PF
5	Allocation of Tasks to PNF
6	Further Breakdown of PF's Tasks
7	Further Breakdown of PNF's Tasks
8	Allocation of Miscellaneous Tasks
9	Clustering and Modeling of PF's Tasks
10	Clustering and Modeling of PNF's Tasks
11	Execution Tasks According to Control Modes 11.1 Modeling of PF's Task Clusters 11.1 Modeling of PNF's Task Clusters

4.2.1. CREW'S GENERIC TASK TYPES

The first step in the breakdown of crew's tasks includes the identification of generic task types of the crew members. For this purpose, the following categories have been established. Per each, a short description is provided. The categories are not presented in any specific order.

1. **Sensing**
   Gathering information needed to get an overview of the location of the aircraft, the surroundings and any nearby traffic.
   Includes: monitoring, looking out the window, listening to party line, getting informed by stewardess.

2. **Integration**
   Connecting the information gathered under 'Sensing', and forming a more elaborated picture of the current situation.
   Includes: summarizing, relating, assessment and understanding of the information.

3. **Prediction**
   Using the elaborated and more global picture of the current situation, formed under 'Integration', to predict future situations and events in support of anticipation.

4. **Complementary communication**
   Aims at verifying a shared awareness, prior to problem solving and planning. The objective is thus to improve and balance crew's understanding of the current situation, and to make sure they all have an identical understanding of the situation.
   Includes communications and consultations, but is not limited to the cockpit boundaries. While pilots may first discuss the problem for possible solutions, contact with outside parties for the purpose of receiving advice is also included. Thus, covers in-cockpit discussions and initial assessment of options, plus communications with other pilots, ATCo and cabin crew.

5. **Problem solving and planning**
   Refers to the consideration of possible solutions, and eventual selection of the most appropriate solution. This, of course, becomes possible through the improved understanding and awareness of crew members.

6. **Executive action**
   Refers to the execution of an actual task by the crew members. It may include implementation of system changes, specific recovery procedures, or input of parameter changes into cockpit instruments.

7. **Rule monitoring**
   Includes monitoring of the implementation of execution actions planned in advance, overall event sequence, and safety of the final status.

8. **Coordination**
   Includes coordination with all human operators in contact with the operation of

the aircraft. Relevant parties include other crew members, ATCo, pilots of other aircraft, and Airline Operation Center (AOC).

9. **overall performance**
   Includes ensuring for a proper execution of all responsibilities. In addition, it includes an assessment of status of all related external systems or parties, and detection of any relevant failure.

10. **Maintenance and monitoring of own part**
    Aims at ensuring that all systems supporting the PF and PNF continue working correctly and remain available in the future.

4.2.2. CREW'S SPECIFIC TASKS

For the purpose of identifying the operation orientated tasks, the following categories of tasks have been established:

i. **Aviate**
   Purpose: To monitor and direct aircraft's attitude, airspeed and altitude, through using the aircraft's flight instruments and controls.
   Includes: All tasks related to maintaining the control of the aircraft.
   Assumptions: Maintenance of separation with the surrounding traffic is not modeled.

ii. **Navigate**
   Purpose: Flying the jet safely towards the final destination.
   Includes: Tasks related to determining the current and target position, heading and flight status, and all obstacles in between. In fact, all navigation and steering tasks relevant to guiding the aircraft from the current point in space to the target point in space shall be considered under navigating.
   Assumptions: Deviations from the cleared route is not modeled; including effects of causes such as closed airport and weather-related issues.

iii. **Communicate**
   Purpose: To ask for, receive and provide instructions and feedback.
   Includes: All communication sub-tasks.
   Assumptions: No internal communication of cockpit-cabin crew, and cockpit-passengers is modeled.

iv. **Miscellaneous**
   Purpose: Complementary means to back up the tasks above in ensuring a safe flight.
   Includes: Manual aircraft operation, security, passenger comfort, etc.
   Assumptions: No other passenger- or technical-related difficulties are included in the modeling.

4.2.3. INTEGRATION OF GENERIC AND SPECIFIC TASKS

This section integrates the 10 generic task types and the four specific tasks, described earlier, for the purpose of identifying the relevant tasks that will be expected of the flight crew throughout the operation. This section does not yet aim at specifying the tasks to any of the two crew members. The specific tasks of Aviate, Navigate, Communicate and Miscellaneous are broken down into their sub-components relevant to each of the ten generic task types.

Remark:
The tasks printed in *italics* are beyond the scope of the modeling of this report.

Table 4.2: Integration of **Aviate** Tasks and **Generic** task types

Generic Task Type	**Aviate Tasks**
1. Sensing	Gather information required for an overall overview of flight and aircraft status. Monitor: assess your aircraft's overall system status, altitude, airspeed, heading, etc. Look out the window. Notice any automated alerts, both verbal and aural.
2. Integration	Connect the gathered information to form a more global picture of aircraft status. Understand and build awareness of any deficiency or improper settings in flight parameters, including altitude, speed and heading; with respect to the flight plan and the issued clearance. Understand and build awareness of any inconsistency in system output.
3. Prediction	Use the global picture to anticipate future potential difficulties and conflicts, and their nature. In the event erroneous readings are detected on a cockpit component, anticipate the incorrect chained feedback to relative (critical) systems.
4. Complementary Communication	Check with the other crew member the awareness and potential countermeasures with regards to the identified issue(s). If advice is desired, contact ATCo. If possible, check and evaluate system output with ATCo's surveillance data.
5. Problem Solving and Planning	Decide on potential solutions, choose appropriate measures and decide on execution procedures. Includes a pre-assessment of the safety of the outcome.
6. Executive Action	In the event of a stall, change AFDS settings; deactivate A/P and A/T. Proceed with the stall recovery procedure. In the event of detecting system failure and inconsistency, ignore the reading from the faulty component. Disengage AFDS components and fly the jet manually, if possible. Change heading, airspeed or altitude, or a combination of these, as required.
7. Rule Monitoring	Check and monitor if corrective tasks have been executed correctly. Are the desired flight status and parameters achieved?

Continued on next page

Continuation of Table 4.2

Generic Task Type	**Aviate Tasks**
	Assess the status of aircraft including flight parameters and aircraft as a whole. Is the flight safe again?
8. Coordination	In the event of severe conflicts, communicate with ATCo. Report on conflict nature and position, and communicate for any assistance needed instantaneously *or on the ground upon landing.* *Communicate with other pilots, if required.*
9. Overall Performance	Ensure overall tasks related to 'Aviate' are properly executed. *Detect failures of ATC surveillance applications, if relevant.*
10. Maintenance and Monitoring of Own System Part	Detect and report failure of aircraft's avionics and cockpit displays; includes means to adjust aircraft settings.
	Concluded

Table 4.3: Integration of **Navigate** Tasks and **Generic** task types

Generic Task Type	**Navigate Tasks**
1. Sensing	Gather information needed to know where you are, where you need to be, and the path to be followed to arrive at target heading and position. Monitor your PFD in order to get instantaneous information on current flight parameters, and potential differences with respect to target parameters. Listen to messages on Radio Transmissions (R/T).
2. Integration	Use the information to get a better image of the flight route, the heading changes and any other system changes required in regards to the clearances given by ATCo.
3. Prediction	Assess the to-be-flown path under uncertain conditions. Anticipate uncertainties and potential deviations as a result of non-stabilized approach, and prepare for countermeasures. *Consider and anticipate possible deviations along the route as a result of unforeseen obstacles. Examples of difficulties leading to a route divergence include problems at airport, passenger- and weather-related issues.*
4. Complementary Communication	Communicate with the other crew member, in order to raise and balance awareness with respect to the anticipated problem and potential solutions. *Contact ATIS or other pilots for further essential information; can include information on weather, runways and approach routes.*
	Continued on next page

Continuation of Table 4.3

Generic Task Type	Navigate Tasks
5. Problem Solving and Planning	Decide if there are strong reasons on why a go-around cannot be executed; for instance, lack of fuel. Otherwise, initiate the go-around procedure, and ensure ATCo is notified.
6. Executive Action	In the event of a go-around, follow the procedure of a go-around and in the meantime, maintain full monitoring of cockpit equipment.
7. Rule Monitoring	Check for appropriate execution of the go-around maneuver. Control the event sequence. Ensure the goal is achieved. In the event of receiving new instructions from ATCo regarding route changes, read-back and confirm the instructions, and implement the new route changes.
8. Coordination	Coordinate the go-around with ATCo, and require a second attempt at landing.
9. Overall Performance	Ensure overall tasks related to 'Navigate' are properly executed. *Detect failure of ATCo in providing proper and on-time assistance.* *Detect failures of technical means and external assistance in detecting obstacles along the route.*
10. Maintenance and Monitoring of Own System Part	Detect failure of aircraft systems in providing appropriate means for aircraft maneuverability. Ensure that all systems related to 'Navigate' are functioning properly.
	Concluded

Table 4.4: Integration of **Communicate** Tasks and **Generic** task types

Generic Task Type	Communicate Tasks
1. Sensing	Gather information to get an overall overview of the status of own aircraft, surroundings, and the airport. Written: Consult available documentation, including flight plan, flight manual and checklists. Verbal: Communicate with and get informed by ATCo, *AOC, other pilots,* other crew member, *and cabin crew members.*
2. Integration	-
3. Prediction	-
4. Complementary Communication	Understand and build up awareness with respect to uncertain difficulties through communicating with the other crew member.
	Continued on next page

Continuation of Table 4.4

Generic Task Type	Communicate Tasks
	Announce intentions on a routine basis. Pass information and acquire more relevant information. Contact ATCo,*ATIS, or AOC* for guidance on making further decisions and taking (corrective) actions.
5. Problem Solving and Planning	-
6. Executive Action	-
7. Rule Monitoring	*Verify that ATCo is fully aware of the traffic- and aircraft-related situations*
8. Coordination	Coordinate with and update ATCo with regards to the new flight or system status. *Update the AOC.* *Update the cabin crew, with regards to the necessary changes implemented, new destination, new time of arrival, etc.* *Update passengers, with regards to the changes in destination or time of arrival.*
9. Overall Performance	Make sure proper and sufficient communication is achieved. Check if ATCo is fully aware of cockpit crew's intentions. *Detect deficiencies of ground means to establish a proper communication.*
10. Maintenance and Monitoring of Own System Part	Detect failure of all communication-related components. *According to safety regulations, report any failure after the flight for maintenance purposes, and inform the crew of next flight through appropriate and available channels.*
	Concluded

Remark:
Miscellaneous tasks should be specific to the operation under study.

Table 4.5: Integration of **Miscellaneous** Tasks and **Generic** task types

Generic Task Type	Miscellaneous Tasks
1. Sensing	Gather information on and observe abnormalities of aircraft and relevant systems and components. *Detect if external or internal physical damage is present.* Listen and look around. Monitor cockpit displays, take note of warnings (for instance, landing gear warning), and R/T messages.

Continued on next page

Continuation of Table 4.5

Generic Task Type	**Miscellaneous Tasks**
	Gather information on and observe any passenger-related issue, including security and health threats, satisfaction, etc.
2. Integration	Use the information to form a global and overall picture of aircraft, technical components and associated software, warnings and their potential causes, *passengers, surrounding traffic and environment.*
3. Prediction	Predict and anticipate potential future hazardous situations. Includes anticipation of potentially unsafe situations; for instance, generation of visual or aural alerts such as landing gear warning, *or consequences of strong crosswinds.* *Includes anticipation of situations such as bird impact, busy traffic, long holding times, fuel shortage, depressurization, etc.*
4. Complementary Communication	Build awareness with respect to the problem at hand and receive guidance on further actions; communicate with other crew member and ATCo/*AOC.*
5. Problem Solving and Planning	Create and plan potential solutions. Decide on techniques to implement the necessary (system) changes, and maneuvers required to solve the conflict. Communicate with ATCo *over route changes, as a result of events such as fuel shortage, depressurization, passenger in serious discomfort, etc.* Assess the situation upon execution of the solution. Is it conflict-free on the short term?
6. Executive Action	Switch on/off engine, A/T, A/P, etc; manually change airspeed, heading or altitude, or a combination of all. Adjust aircraft's movement through operation of rudder, flaps, throttle levers, etc. *Other changes include, but are not limited to, cabin area changes such as temperature, lightning, engine settings, etc.*
7. Rule Monitoring	Control the execution of solutions, event sequence and flight maneuvers. Check if a safe and desired flight condition is achieved.
8. Coordination	Coordinate with ATCo on significant malfunctioning and system failures. Coordinate with and update ATCo about new system status. *Update AOC of any significant flight changes, abnormal aircraft performance, etc.* *Update cabin crew of necessary changes implemented; new destination, arrival route, etc.* *Update passengers of changes made to the flight.*
9. Overall Performance	Assess the other crew member's ability in properly executing necessary tasks in keeping the flight safe.

Continued on next page

Continuation of Table 4.5

Generic Task Type	**Miscellaneous Tasks**
	Assess if the overall aircraft performance is as expected. *Detect ATCo's inability or delayed response in providing sufficient assistance.*
10 Maintenance and Monitoring of Own System Part	Detect and report system failures.
	Concluded

4.2.4. ALLOCATION OF TASKS TO PF

This section will transfer the overall integrated task lists given in Section 4.2.3 into the tasks applicable to the PF only. The same procedure will be applied for an allocation of tasks to the PNF, to be found in Section 4.2.5.

In order to establish a hierarchical breakdown of the tasks, and for the purpose of representing the significance of the more critical tasks compared to those deemed as less or non-critical, the following categorization of tasks is applied (NLR, 2009):

A/B Explicit and Critical tasks
: Includes all tasks considered as PF's primary tasks; those tasks with significant influence on the safety of the flight. A more detailed distinction between the explicit tasks will be provided in Section 4.2.6.

C Non-Critical tasks
: This primarily includes PF's noncritical and secondary tasks. It also covers tasks which are, under normal operating circumstances, primarily considered as PNF's tasks, but where PF steps in or is forced to act as back up. This illustrates a condition in which the PF may challenge the PNF, take over his or her responsibility if required, or provide assistance to PNF if requested (NLR, 2009).

D Not Applicable
: This includes all tasks which, under normal operating circumstances, are not initially considered as a task of the PF. He or she might however be forced to perform these under exceptional conditions.

Tables 4.6 to 4.8 allocate the tasks to the PF. This covers the allocation of tasks related to the 'Aviate', 'Navigate', and 'Communicate' categories. The allocation of 'Miscellaneous' sub-tasks, to both the PF and the PNF, will be outlined in Section 4.2.8. Per task, three dimensions are applied. These consist of the generic and specific task types, along with the significance of the task according to the significance scheme introduced above.

Remark
The tasks printed in *italics* are beyond the scope of the modeling of this report.

Table 4.6: Allocation of integrated **Aviate** tasks and **Generic** task types to PF. The column 'Sign' indicates the significane.

Generic Task Types	Aviate Tasks	Sign.
1. Sensing	Notice any automated alerts, both verbal and aural.	A/B
	Gather information required for an overall overview of flight and aircraft status.	C
2. Integration	Understand and build awareness of the flight difficulty, or of any inconsistency in system output.	A/B
	Connect the gathered information to form a more global picture of aircraft.	C
3. Prediction	Use the global picture to anticipate future potential difficulties, and their natures. Upon detection of erroneous readings, anticipate incorrect chained feedback to potential corresponding system(s).	C
	Assess, or communicate with PNF, the wrong chained feedback of faulty device(s) into AFDS components, if applicable.	D
4. Complementary Communication	Check and balance awareness of identified issue(s) and potential relevant measures with PNF. If advice is desired, request contact with ATCo.	C
5. Problem Solving and Planning	Plan for the corrective action(s). Assess the efficiency of the solution(s) and safety of the outcome.	A/B
	Create potential solutions, choose the appropriate solution and decide on execution possibilities.	C
	Communicate the task distribution during the execution and monitoring of the solution procedure, with the PNF.	C
6. Executive Action	When stick shaker activated, initiate and execute stall recovery procedure. Disengage A/P & A/T, push throttle levers to maximum, pitch down to increase velocity, followed by a pitch up.	A/B
	When observing (LRRA) output inconsistencies, ignore the readings from faulty component. Disengage A/P and A/T, and fly manually, if applicable.	A/B
7. Rule Monitoring	Monitor the execution of corrective tasks and event sequence.	A/B
	Assess the new aircraft status. Is the flight safe?	C
8. Coordination	In the event of severe safety threats, report to ATCo on current position and the conflict nature. Communicate any assistance required instantaneously (R/T) *or on the ground,* to ATCo.	D

Continued on next page

Continuation of Table 4.6

Generic Task Types	Aviate Tasks	Sign.
	Communicate over severe and specific conflict with pilots of other aircraft.	D
	Communicate with and inform cabin crew and passengers of possible impact.	D
9. Overall Performance	Ensure overall tasks related to 'Aviate' are properly executed.	C
10. Maintenance and Monitoring of Own System Part	Detect failure of aircraft's avionics, including means to maneuver in the air.	A/B
	According to emergency procedures, report failure of aircraft's avionics in writing after flight.	C
		Concluded

Table 4.7: Allocation of integrated **Navigate** tasks and **Generic** task types to PF

Generic Task Types	Navigate Tasks	Sign.
1. Sensing	Continuously gather information related to an overview of current status of completion of approach checklist. Observe the information available on PFD, R/T messages, and flight plan, regarding runway alignment and interception of the glide slope.	C
	Notice any other automated alerts. Observe any unexpected occurring, which can potentially jeopardize and influence the route planned in flight plan; for instance, while approaching a thunderstorm.	D
2. Integration	Comprehend the phase of approach and realize any potential deficiencies in stabilization of the approach. If deficiencies are detected, understand that from a safety perspective, the approach should not be completed.	A/B
	Form a global picture of the flight status*, and possible deviations from planned route.*	C
3. Prediction	Assess the ability to stabilize the aircraft in time for a safe continuation of approach.	A/B
	Anticipate approach uncertainties and relevant safety concerns following an non-stabilized approach, and prepare for countermeasures.	C
	Assess the originally planned route under potential difficulties and possible deviations; for instance, while approaching a thunderstorm.	C
		Continued on next page

Continuation of Table 4.7

Generic Task Types	**Navigate Tasks**	**Sign.**
4. Complementary Communication	Communicate and balance awareness with PNF on the unstable nature of approach and the potential solutions.	C
	Consult ATIS for information on environmental factors.	D
5. Problem Solving and Planning	Decide if there are strong reasons why a go-around cannot be executed. Otherwise, confirm the go-around. Assess if the path is safe on short-term.	A/B
	Consult ATCo, plan for a second attempt. Assess if the path is safe on short-term. Coordinate further limitations and route divergences with ATCo.	C
	Notify ATCo of the decision on the go-around. Coordinate with ATCo *and plan for the execution of the maneuver.*	D
6. Executive Action	*Initiate and conduct the go-around procedure. Adjust the airspeed, throttle levers, landing gears and flaps accordingly. Make use of the TO/GA switch, if applicable.*	A/B
7. Rule Monitoring	*Check the execution of the go-around maneuver and the corresponding event sequence.*	A/B
	Check if the approach is safely aborted and that the aircraft has gained sufficient altitude and airspeed.	C
8. Coordination	*Coordinate with and be advised by ATCo on the remainder of the approach.*	C
	Communicate the route changes and consequences with AOC.	C
	Communicate the aborted approach to cabin crew and inform the passengers of the situation.	D
9. Overall Performance	Ensure overall tasks related to 'Navigate' are properly executed.	C
	Assess ATCo's and ATIS's ability in providing continuous and real-time information on route obstacles.	D
	Detect ATCo's failure in providing proper and on-time assistance.	D
10. Maintenance and Monitoring of Own System Part	Detect failure of own navigation systems and related components.	A/B
	According to emergency requirements, report failure of aircraft's avionics in writing after the flight.	C
		Concluded

Table 4.8: Allocation of integrated **Communicate** tasks and **Generic** task types to PF

Generic Task Types	**Communicate Tasks**	**Sign.**
1. Sensing	Gather information to get an overview of the flight situation. Consult documentation, flight plan, checklists, R/T messages and automated alerts.	C
	Take notice of cabin crew's safety-related remarks.	D
2. Integration	-	
3. Prediction	-	
4. Complementary Communication	Pass information to and acquire more relevant information from the PNF, in order to raise awareness over any potential difficulty.	C
	Consult ATCo/*ATIS/AOC* if required, in order to gain more insights on further course of action.	D
5. Problem Solving and Planning	-	
6. Executive Action	-	
7. Rule Monitoring	*Verify that ATCo is fully aware of traffic- and aircraft-related potential issues.*	D
8. Coordination	Coordinate the new established status or flight route with ATCo, and establish further contacts if needed.	D
	Communicate the changes with AOC.	D
	Inform and update cabin crew and passengers, regularly.	D
9. Overall Performance	Ensure sufficient level of communication is present at all times.	A/B
	Ensure overall tasks related to 'communicate' are properly executed.	C
	Detect failures of ground-based infrastructure responsible for providing continuous ground-air communication. Furthermore, assess if the ATCo is fully responsive, or if the ATIS is providing real-time information.	D
10. Maintenance and Monitoring of Own System Part	Ensure all communication-related components are functioning properly. Detect any failure.	C
	Report the failure of any communication-related component.	D
		Concluded

4.2.5. ALLOCATION OF TASKS TO PNF

The tasks applicable to the PNF are identified in a similar manner to that of the PF, with a minor change in the hierarchical breakdown. As it can be seen below, the tasks applicable to the PNF are categorized in only two steps, namely explicit and secondary tasks. A description of these two are given below:

A/B Explicit tasks
Including all tasks considered as PNF's primary tasks.

C Secondary tasks
This includes all tasks, which are considered as PNF's responsibilities under normal operating circumstances. A PF may however be required to step in and act as back up. This illustrates a condition in which the PF may challenge the PNF, take over the responsibility or assist the PNF if requested (NLR, 2009).

Similar to Section 4.2.4, each task is associated with a generic and a specific task type, along with an indication of the significance of the task. The results are provided in Tables 4.9 to 4.11.

Remark
The tasks printed in *italics* are beyond the scope of the modeling of this report.

Table 4.9: Allocation of integrated **Aviate** tasks and **Generic** task types to PNF

Generic Task Types	**Aviate Tasks**	**Sign.**
1. Sensing	Gather information required for an overall overview of the flight status. Notice any automated alerts.	C
2. Integration	Form a more global picture of the flight. Understand any possible flight difficulty and inconsistency in system outputs.	C
3. Prediction	Anticipate future potential difficulties, and their natures. Upon detection of erroneous readings, anticipate the incorrect chained feedback to the relative system(s) with the help of the PF.	C
4. Complementary Communication	Check with PF and balance awareness on any identified issue and potential relevant measures. If advice is desired, or if requested by the PF, establish contact with ATCo.	C
5. Problem Solving and Planning	Create potential solutions and assess the safety of the outcome. *Communicate the task distribution during the process with the PF.*	C
6. Executive Action	-	
7. Rule Monitoring	Monitor the execution of corrective tasks and the event sequence. Is the new flight status safe?	C
Continued on next page		

Continuation of Table 4.9

Generic Task Types	Aviate Tasks	Sign.
8. Coordination	In the event of severe safety threats, report to ATCo on position and conflict nature, and communicate over any assistance required instantaneously *or on the ground.*	A/B
	Communicate over any severe and specific conflict with other pilots, if applicable. Communicate and inform cabin crew and passengers of possible impact.	C
9. Overall Performance	Ensure overall tasks related to 'Aviate' are properly executed.	C
	Detect failures of the ATC infrastructure and of the ATCo.	C
10. Maintenance and Monitoring of Own System Part	Detect failure of own aircraft's avionics, including means to maneuver in the air.	A/B
		Concluded

Table 4.10: Allocation of integrated **Navigate** tasks and **Generic** task types to PNF

Generic Task Types	Navigate Tasks	Sign.
1. Sensing	Continuously gather information related to an overview of current and target flight status and attitudes. Observe the information available on PFD, R/T messages, and flight plan.	A/B
	Notice any other automated alerts. Observe any unexpected occurring, which can potentially jeopardize and influence the route planned in flight plan; for instance, approaching a thunderstorm.	C
2. Integration	Form a global picture of the flight status. Comprehend the phase of approach and realize any deficiencies in stabilization of the approach. If deficiencies are detected, understand that from a safety perspective, the approach should not be completed.	A/B
3. Prediction	Anticipate uncertainties and relevant safety concerns following a non-stabilized approach, and prepare for countermeasures.	A/B
	Assess the originally planned route under potential difficulties and possible deviations; for instance, due to a thunderstorm.	A/B
4. Complementary Communication	Communicate and balance awareness with PF about the anticipated problem and potential solutions. *Consult ATIS for information on environmental factors.*	A/B
5. Problem Solving and Planning	Decide if there are strong reasons why a go-around cannot be executed.	A/B
		Continued on next page

Continuation of Table 4.10

Generic Task Types	Navigate Tasks	Sign.
	In the event of a go-around, establish contact with ATCo and notify the controller of the decision. *Coordinate with ATCo and Plan for the execution of the maneuver. Assess if the path is safe on short-term, and plan for the execution of the maneuver.*	A/B
6. Executive Action	*Assist the PF in initiation and execution of the go-around procedure. Monitor the status of the flight throughout the operation, and warn the PF of any deficiencies in completion of the procedure.*	
7. Rule Monitoring	*Monitor the event sequence. Is the approach safely aborted and has the aircraft gained sufficient altitude and airspeed?*	A/B
8. Coordination	*Coordinate with and be advised by ATCo on the remainder of the approach. Communicate the route changes and possible consequences with AOC. Communicate the aborted approach to cabin crew and inform the passengers of the situation.*	A/B
9. Overall Performance	Ensure overall tasks related to 'Navigate' are properly executed. *Assess the PF's judgment of the call on go-around.*	A/B
	Detect ATCo's failure in providing proper and on-time assistance. Detect ATCo's and ATIS's ability in providing continuous and real-time information with regards to route obstacles.	A/B
10. Maintenance and Monitoring of Own System Part	Detect failure of own navigation systems.	A/B
		Concluded

Table 4.11: Allocation of integrated **Communicate** tasks and **Generic** task types to PNF

Generic Task Types	Communicate Tasks	Sign.
1. Sensing	Gather information to get an overview of the flight status. Consult documentations, flight plan, checklists, R/T messages and automated alerts.	A/B
	Take notice of cabin crew's safety-related remarks.	A/B
2. Integration	-	
3. Prediction	-	
4. Complementary Communication	Pass information to and acquire more relevant information from the PF with regards to potential difficulties.	A/B
	Consult ATCo, *ATIS or AOC* if required, gain insights on further course of action.	C
		Continued on next page

Continuation of Table 4.11

Generic Task Types	Communicate Tasks	Sign.
5. Problem Solving and Planning	-	
6. Executive Action	-	
7. Rule Monitoring	Check if PF has fully received and acknowledged ATCo's instructions. *Verify that ATCo is fully aware of traffic- and aircraft-related potential issues.*	A/B
8. Coordination	Coordinate the new established flight status or route, and establish further contacts if required.	A/B
	Establish contact and communicate the flight plan changes with AOC. Inform and update cabin crew and passengers, regularly.	A/B
9. Overall Performance	Ensure sufficient level of communication is present at all times, and that the overall 'communication' tasks are properly executed.	A/B
	Detect failure of ground-based infrastructure to establish continuous communication.	A/B
10. Maintenance and Monitoring of Own System Part	Ensure all communication-related components are functioning properly. Detect any failure.	A/B
		Concluded

4.2.6. FURTHER BREAKDOWN OF PF'S TASKS

In order to further break down the task types associated to the PF, this section makes an additional distinction in between the tasks considered as critical tasks of the PF in Section 4.2.4. Through an indication of the availability of a generated alert, critical tasks for which the crew get a notification are separated from critical tasks for which the crew will have to use own judgment and cognitive understanding to react upon. The following dimension is thus added to the earlier task categorization of Section 4.2.4:

A **Critical and Explicit** task,

On the basis of knowledge becoming available to the PF, from all sources except for the automated alerts.

B **Critical and Explicit** task,

On the basis of knowledge derived from the automated alerts. Described earlier in Chapter 3, the warning systems applicable within the scope of this report include aural warnings of low airspeed and landing gear configuration, in addition to visual warnings related to loss of altitude and airspeed, illustrated on the PFD's available in front of the cockpit crew members.

C Non-Critical task,

Includes back-up tasks and additional tasks applicable to the specific scenario and relevant event sequence.

For Tables 4.12 to 4.14, the tasks defined in the previous steps which fall outside the scope of this report have been omitted from further analysis. It should be realized that, various 'critical' tasks may be broken down into components under both A and B, indicating that in addition to the generated warnings and external triggers, the crew can use their equipment and other means to update their SA's of these critical tasks.

Table 4.12: Further breakdown of PF's integrated **Aviate** tasks and **Generic** task types

Generic Task Types	**Aviate Tasks**		
	A	**B**	**C**
1. Sensing		Notice automated alerts, both verbal and aural.	Gather information for an overview of flight status. Spot differences in system outputs.
2. Integration	Understand flight difficulty, and any inconsistency in system outputs.	Understand flight difficulty, and any inconsistency in system output.	Form a more global picture of aircraft performance.
3. Prediction		Anticipate future potential difficulties and their natures.	Upon detection of erroneous readings, identify systems to be potentially affected by faulty inputs.
			Assess consequences of the erroneous chained feedback of the faulty device(s) into the AFDS components.
4. Complementary Communication			Check awareness of identified difficulty with PNF. Request contact with ATCo, if needed.
5. Problem Solving and Planning		Plan for the corrective action(s) relevant to the present conflict. Assess the safety of the outcome.	Create potential solutions, choose the appropriate solution and decide on execution possibilities.

Continued on next page

Continuation of Table 4.12

Generic Task Types	**Aviate Tasks**		
	A	**B**	**C**
6. Executive Action		In the event of a decision on a stall recovery, execute the procedure.	
		In regard to LRRA output inconsistencies, ignore the RA outputs on the PFD's. Disengage automatic flight, possibly steer, climb or descend, or change airspeed, as appropriate.	
7. Rule Monitoring	Control event sequence of corrective actions.	Is the new status safe? Take note of any (new) generated alerts.	
8. Coordination			Report to ATCo on the position and conflict nature, ask for any assistance needed.
9. Overall Performance			Ensure Aviate-related tasks are all properly executed.
10. Maintenance and Monitoring of Own System Part	Detect failure of avionics systems when abnormalities are detected on cockpit screens.	Detect failure of avionics systems, upon detection of visual or aural warnings.	
			Concluded

Table 4.13: Further breakdown of PF's integrated **Navigate** tasks and **Generic** task types

Generic Task Types	**Navigate Tasks**		
	A	**B**	**C**
1. Sensing			Gather information for an overview of the completion of approach checklist.
2. Integration	In the event of a non-stabilized approach, understand that the approach may not be completed.		Comprehend the current phase of approach, and realize any potentially deficient execution of approach stabilization.
			Form a global picture of the status of the flight, and of the aircraft as a whole system.
3. Prediction			Anticipate flight uncertainties and relevant safety concerns, arising from a non-stabilized approach.
4. Complementary Communication			Balance cockpit awareness regarding the non-stabilized nature of the approach.
5. Problem Solving and Planning	Assess if a go-around is impractical. If no limitations, confirm the go-around.	Assess if a go-around is impractical. If no limitations, confirm the go-around.	Request contact with ATCo, with the purpose of notifying the ATCo of the go-around.
6. Executive Action			
7. Rule Monitoring			
8. Coordination			
9. Overall Performance			Ensure that Navigate-related tasks are all properly executed.

Continued on next page

Continuation of Table 4.13

Generic Task Types	Navigate Tasks		
	A	**B**	**C**
10. Maintenance and Monitoring of Own System Part	Detect failure of avionics systems when abnormalities are detected on the cockpit screens.	Detect failure of avionics systems, upon detection of visual or aural warnings.	
			Concluded

Table 4.14: Further breakdown of PF's integrated **Communicate** tasks and **Generic** task types

Generic Task Types	Communicate Tasks		
	A	**B**	**C**
1. Sensing			Consult sources of information, for the purpose of obtaining an overview of relative flight situation; includes both written and verbal communications.
2. Integration			
3. Prediction			
4. Complementary Communication			Raise the awareness of the cockpit crew regarding potential difficulties, through sharing information with PNF.
			Request contact and consultation with ATCo, if needed.
5. Problem Solving and Planning			
6. Executive Action			
7. Rule Monitoring			
			Continued on next page

Continuation of Table 4.14

Generic Task Types	Communicate Tasks		
	A	**B**	**C**
8. Coordination			Request contact with ATCo, for the purpose of coordinating extreme recovery measures in the event of critical conflicts.
9. Overall Performance			Ensure sufficient communications at all times, within the cockpit and air-to-ground.
			Ensure that Communicate-related tasks are properly executed.
10. Maintenance and Monitoring of Own System Part			Ensure that components of Communications are working properly. Detect any possible failure.
			Concluded

4.2.7. FURTHER BREAKDOWN OF PNF'S TASKS

In a similar manner, the tasks associated to the PNF in Section 4.2.5 are further broken down according to the second categorization of tasks applied to the PF's tasks. For convenience of the reader, the categories are once again presented below. The same method applied in the previous section is applied for the representation of the categories.

A Critical and **Explicit** tasks

On the basis of knowledge becoming available to the PF, from all sources except for the automated alerts.

B Critical and **Explicit** tasks

On the basis of knowledge derived from the automated alerts. Described earlier in Chapter 3, the warning systems applicable within the scope of this report include aural warnings of low airspeed and landing gear configuration, in addition to visual warnings related to loss of altitude and airspeed, illustrated on the PFD's available in front of the cockpit crew members.

C Non-Critical tasks

Includes back-up tasks and additional tasks applicable to the specific scenario and relevant event sequence.

Table 4.15: Further breakdown of PNF's integrated **Aviate** tasks and **Generic** task types

Generic Task Types	**Aviate Tasks**		
	A	**B**	**C**
1. Sensing		Notice automated alerts, both verbal and aural.	Gather information for an overview of flight and aircraft status. Spot differences in system outputs.
2. Integration			Form a more global picture of aircraft performance. Understand flight difficulty, and any inconsistency in system output.
3. Prediction			Anticipate future difficulties and their natures.
			Anticipate and Identify consequences of erroneous readings on relative systems.
4. Complementary Communication			Check awareness of identified difficulty with PF.
			Contact ATCo, if needed or requested by PF.
5. Problem Solving and Planning			Create and choose potential solutions. Assess safety of the outcome.
6. Executive Action			
7. Rule Monitoring			Check execution of the corrective actions and the event sequence. Is the flight safe?

Continued on next page

Continuation of Table 4.15

Generic Task Types	Aviate Tasks		
	A	B	C
8. Coordination	Report current position and the conflict nature to ATCo, and acquire further assistance.		
9. Overall Performance			Ensure Aviation-related tasks are all properly executed.
10. Maintenance and Monitoring of Own System Part	Detect failure of avionics systems when abnormalities are detected on cockpit screens.	Detect failure of avionics systems, upon detection of visible or aural warnings.	
			Concluded

Table 4.16: Further breakdown of PNF's integrated **Navigate** tasks and **Generic** task types

Generic Task Types	Navigate Tasks		
	A	B	C
1. Sensing	Continuously gather information regarding position, velocity, and completion status of approach checklist.		
2. Integration	Form a global picture of flight status. Comprehend the progress made along the final approach, and realize any potential deficient execution of approach stabilization.		
	In the event of a non-stabilized approach, understand that approach should not be completed.		
			Continued on next page

Continuation of Table 4.16

Generic Task Types	Navigate Tasks		
	A	B	C
3. Prediction	Anticipate uncertainties and safety concerns in regards to a non-stabilized approach.		
4. Complementary Communication			Check awareness of the conflict and the necessity of a go-around with the PF.
5. Problem Solving and Planning	if no limitations, assess the practicability of a go-around.	Assess if go-around cannot be executed.	
	Initiate contact with and notify ATCo.		
6. Executive Action			
7. Rule Monitoring			
8. Coordination			
9. Overall Performance			Ensure that Navigation-related tasks are all properly executed.
10. Maintenance and Monitoring of Own System Part	Detect failure of avionics systems when abnormalities are detected on cockpit screens.	Detect failure of avionics systems, upon detection of visible or aural warnings.	
			Concluded

Table 4.17: Further breakdown of PNF's integrated **Communicate** tasks and **Generic** task types

Generic Task Types	**Communicate Tasks**		
	A	**B**	**C**
1. Sensing			Consult sources of information for an overview of relative aircraft and flight situation; includes both written and verbal communications.
2. Integration			
3. Prediction			
4. Complementary Communication			Raise awareness with regards to potential difficulties, through sharing information with the PF.
			Consult with ATCo, if required.
5. Problem Solving and Planning			
6. Executive Action			
7. Rule Monitoring	Ensure PF receives and fully understands ATCo's clearances.		
8. Coordination			Coordinate any new flight status or route changes with ATCo.
9. Overall Performance	Ensure sufficient communications, and a proper execution of all Communication-related tasks.		
10. Maintenance and Monitoring of Own System Part			Detect failure of own communication systems.
			Concluded

4.2.8. ALLOCATION OF MISCELLANEOUS TASKS

For the purpose of breaking down the miscellaneous tasks, the same categories used in Sections 4.2.6 and 4.2.7 is applied to the miscellaneous tasks described earlier in Section 4.2.8. It should be noted that miscellaneous tasks defined in Section 4.2.8 that are outside the scope of this report are not included under the categorization in this section.

Table 4.18: Allocation of integrated **Miscellaneous** tasks and **Generic** task types to PF

Generic Task Types	**Miscellaneous Tasks**		
	A	**B**	**C**
1. Sensing		Notice automated warnings.	
2. Integration	Understand the potential cause, if possible.	Understand the potential cause, if possible.	
3. Prediction		Anticipate possible consequences.	
4. Complementary Communication	Check awareness with PNF.		Request contact and reporting of the issue to ATCo, if needed.
5. Problem Solving and Planning		Decide on neglecting or correcting for the warning, according to understanding of situation and anticipation of potential consequences.	
6. Executive Action		Respond to the warnings, if applicable; for instance, extend the landing gears.	
		Otherwise, disengage automatic flight, possibly change altitude and thrust level.	
7. Rule Monitoring		Check for a correct implementation of corrective actions and system changes, as appropriate.	
8. Coordination			Request coordination or initiate coordination with ATCo, upon detection of serious conflicts.

Continued on next page

Continuation of Table 4.18

Generic Task Types	Miscellaneous Tasks A	Miscellaneous Tasks B	Miscellaneous Tasks C
9. Overall Performance			
10. Maintenance and Monitoring of Own System Part			Detect possible failures.
Concluded			

Table 4.19: Allocation of integrated **Miscellaneous** tasks and **Generic** task types to PNF

Generic Task Types	Miscellaneous Tasks A	Miscellaneous Tasks B	Miscellaneous Tasks C
1. Sensing		Notice automated warnings.	
2. Integration			
3. Prediction			
4. Complementary Communication	Check awareness with PF.		
	Initiate contact with ATCo, if considered necessary, or if requested by PF.		
5. Problem Solving and Planning		Coordinate with and assist the PF in planning for a corrective measure with regards to the problem at hand.	
6. Executive Action			
7. Rule Monitoring			
8. Coordination	Ensure appropriate and on-time communications with ATCo, in the event of any serious conflict.		
9. Overall Performance			

Continued on next page

Continuation of Table 4.19

Generic Task Types	**Miscellaneous Tasks**		
	A	**B**	**C**
10. Maintenance and Monitoring of Own System Part			Detect component failures.
			Concluded

4.2.9. CLUSTERING AND MODELING OF PF'S TASKS

The breakdown of the tasks, up to Section 4.2.8, has so far established an individual mapping of tasks to each pilot taking into account his or her flight responsibilities. This section aims at grouping PF's individual tasks and transferring them into relevant task clusters. The following properties (NLR, 2009) will be applicable to the tasks within the same task cluster:

Property 1 to be executed sequentially,
Property 2 assigned with the same priority,
Property 3 will equally influence the overall functionality of the aircraft and the safety of the flight.

Keeping in mind the cluster properties above, the following clusters of tasks have been identified for the PF:

PF_i: Conflict Sensing
PF_{ii}: Stall Recovery
PF_{iii}: Sensor Failure Resolution
PF_{iv}: Go-Around
PF_v: Speed Conflict Resolution
PF_{vi}: Back-up the PNF
PF_{vii}: Emergency Actions
PF_{viii}: Miscellaneous

The breakdown and description of each task cluster is detailed below. Per each cluster, the relevant tasks can be found as follows. The three letter acronym represents one of the four specific task types, introduced in Section 4.2.2, namely Aviate (AVI), Navigate (NAV), Communicate (COM) and Miscellaneous (MIS). In addition, each task is represented as a combination of a letter and a number, where the former refers to the significance level introduced in Section 4.2.6 and the latter referring to the generic task type, introduced in Section 4.2.1.

Next, a description of the relevance of the cluster to the operation is given, along with any necessary remarks.

Table 4.20: PF's task cluster PF_i: **Conflict Sensing**

Cluster:	**Conflict Sensing**
Tasks Included	**AVI**: B1, C1 **NAV**: C1, C2 **MIS**: B1
Relates to:	A conflict has been developing, and requires FP's immediate action. Otherwise, it may severely affect the functionality and safety of the flight.
Includes:	Continuously monitor cockpit equipment and notice any generated alert. Notice any indications of insufficient flight performance, sensor or system failure, or deficient progresses regarding completion of checklists and other flight duties. Take note of visual warnings illustrated on the PFD. Watch out for contradicting readings of altitude and airspeed on the PFD. In addition, detect and comprehend the reasoning behind the activation of visual and aural warnings.
Remarks:	One should realize that the PF is not warned about a non-stabilized approach; it is to be comprehended by the PF.
	Concluded

Table 4.21: PF's task cluster PF_{ii}: **Stall Recovery**

Cluster:	**Stall Recovery**
Tasks Included	**AVI**: B2, B3, C4, B5, B6(a), B7
Relates to:	Insufficient or late detection of loss of airspeed. Both the PF and PNF have failed in detecting the airspeed loss earlier. The aircraft has lost its speed to the point that the speed is beyond the minimal operating speed, where the occurrence of stall is considered irreversible. The stick shaker is activated next.
Includes:	Observe and comprehend the insufficient airspeed from the stick shaker warning. Understand the stall conflict. Raise awareness about stall through communication with the PNF. Decide on and initiate the execution of the stall recovery procedure. Disengage automatic flight components, and proceed as established in the procedure. In the meantime, check execution of the steps and the event sequence. Check if the conflict is clear and if sufficient airspeed and altitude have been achieved.
Remarks:	1. At the moment the stall is understood, the PF will remain focused on the execution of the stall recovery. As such, he or she shall not initiate a different task before appropriate speed beyond the stall boundary has been achieved.
	Continued on next page

Continuation of Table 4.21

Cluster:	**Stall Recovery**
	2. The distribution of tasks in between the PF and the PNF is assumed to have been established beforehand. As such, the PF shall remain the sole controller in executing critical components of a stall recovery. 3. A complete execution of a stall recovery is considered sufficient to safely bring the aircraft back onto the route to continue its approach. As such, no further navigation tasks are required by the PF.
	Concluded

Table 4.22: PF's task cluster PF_{iii}: **Sensor Failure Resolution**

Cluster:	**Sensor Failure Resolution**
Tasks Included	**AVI**: B2, C2, C3, C4, B5, C5, B6(b), B7
Relates to:	Failure of on-board sensors, including the failure of the left LRRA.
Includes:	Having noticed the inconsistency in between the RA readings on the two PFD's, understand the untrustworthy indications of the altitude, check awareness with PNF, and achieve a shared realization of a faulty LRRA as the potential cause. Assess and comprehend the consequence of a wrong RA feedback on the remainder of the cockpit instruments. Understand the potential influence on the A/T. Create potential solutions and decide on execution of a resolution task. Proceed by ignoring the RA output, disengaging the automatic flight components, and flying the jet manually. Possibly climb or descend, with possible changes of aircraft's airspeed and heading. Regardless, maintain an uptodate SA of flight parameters. Is the flight safe?
Remarks:	The LRRA sensor failure is not considered by the PF as a critical and unsafe condition. As such, the PF shall remain vulnerable to distractions which could potentially deviate him or her from the course of actions intended for the resolution of the LRRA-related conflict.
	Concluded

Table 4.23: PF's task cluster PF_{iv}: **Go-Around**

Cluster:	**Go-Around**
Tasks Included	**NAV**: A2, C2, C3, A4, C4, B5
Relates to:	Failure of crew in achieving a stabilized approach, causing the need to avoid the approach and perform a go-around.
Includes:	Having assessed and realized the non-stabilized approach upon reaching an altitude of 1,000 ft, understand the need for an abortion of the approach based on the safety regulations. Communicate with PNF. Asses if it may still be safe or necessary to continue the approach. Otherwise, confirm the go-around and request for communication of the decision to ATCo.
Remarks:	Similar to cluster PF_{iii}, the PF remains the pilot in charge responsible for the issue and execution of the go-around.
	Concluded

Table 4.24: PF's task cluster PF_v: **Speed Conflict Resolution**

Cluster:	**Speed Conflict Resolution**
Tasks Included	**AVI**: B2, B3 C4, B5, B6(a), B7
Relates to:	Observation of insufficient and low flight airspeed. Aircraft is flying significantly slower than the intended airspeed, and visual warnings of low airspeed have emerged on the PFD display. The aircraft is not yet in a definite stall condition, and the stick shaker has not yet been activated.
Includes:	Comprehend the meaning of the visual warnings. Check understanding of the conflict with PNF, and decide on conflict resolution. Execute the appropriate solution. It should include disengaging the automatic flight system, adjusting the level of generated thrust, possibly combined with changes in altitude or heading. Check the execution of the corrective actions at all time. Check if the conflict is clear.
Remarks:	None.
	Concluded

Table 4.25: PF's task cluster PF_{vi}: **Back-up the PNF**

Cluster:	**Back-up the PNF**
Tasks Included	**AVI**: C4, C5, C8, C9 **NAV**: C1, C4, C9
	Continued on next page

Continuation of Table 4.25

Cluster:	**Back-up the PNF**
	COM: C1, C4, C8, C9 **MIS**
Relates to:	Taking over the PNF's tasks. Execution of communication duties or implementation of changes to avionics or control surfaces.
Includes:	In the event of a critical conflict, and upon PNF's failure in properly and thoroughly completing his or her tasks, PF steps in to take over the PNF's responsibility. Includes initiation of communications with the ATCo, reporting possible flight conflicts, and receiving relative instructions. In addition, it includes implementation of changes to avionics or control surfaces, such as flaps.
Remarks:	As it was described earlier in the methodology and scope of this report, the analysis considers the functionality of a healthy and standard 2-seat cockpit in which the PF and PNF are fully present and active in the cockpit throughout the entire duration of the flight. The PNF is thus considered capable of performing the tasks associated to him or her, and such, this cluster is considered irrelevant for the remainder of the performance modeling.
	Concluded

Table 4.26: PF's task cluster PF_{vii}: **Emergency Actions**

Cluster:	**Emergency Actions**
Tasks Included	**AVI**: A10, B10, **NAV**: A10, B10, **COM**: C10, **MIS**: C10
Relates to:	The situation in which the main functions cannot be completed, due to significant on-board component failures.
Includes:	Take notice of abnormalities and malfunctioning, realize the resulting limitations in functionality of the aircraft. Consider the relevant emergency procedures, and act accordingly. It may include possible steering, change of thrust, heading or altitude, or operation of flaps and landing gears.
Remarks:	None.
	Concluded

Table 4.27: PF's task cluster PF_{viii}: **Miscellaneous**

Cluster:	**Miscellaneous**
Tasks Included	**AVI**: C9, A10, B10, **NAV**: A10, B10, **COM**: C9, C10, **MIS**
Relates to:	The remainder of the tasks applicable to the PF, not yet covered under the previous clusters.
Includes:	Ensure a proper and sufficient execution of tasks related to Aviation, Navigation and Communication. Detect any limitations jeopardizing a proper execution of the three specific task types. Fulfill the remainder of tasks associated to the PF.
Remarks:	None.
	Concluded

4.2.10. CLUSTERING AND MODELING OF PNF'S TASKS

This section incorporates the same methodology of Section 4.2.9 in order to cluster and model the tasks applicable to the PNF.

Tasks in the same cluster will benefit from the same properties as those applicable to PF's task clusters, described in Section 4.2.9. The following task clusters have been identified for the PNF, to be described in details below:

- PNF_i: Failure Sensing
- PNF_{ii}: Stall Recovery
- PNF_{iii}: Speed Conflict Resolution Monitoring
- PNF_{iv}: Sensor Failure Resolution Monitoring
- PNF_v: Go-Around Monitoring
- PNF_{vi}: Emergency Actions
- PNF_{vii}: Air-Ground Communication
- PNF_{viii}: Miscellaneous

Table 4.28: PNF's task cluster PNF_i: **Failure Sensing**

Cluster:	**Failure Sensing**
Tasks Included	**AVI**: B1, C1, A10, B10, **NAV**: A10, B10, **COM**: C1, A10, B10, **MISC**: B1, C10
Relates to:	Failures have occurred within the avionics components. This cluster relates to assessing the ability of the crew in detecting failures.
	Continued on next page

Continuation of Table 4.28

Cluster:	**Failure Sensing**
Includes:	Detect failures of on-board systems, to include the mismatching outputs of the LRRA's. In addition, understand limitations in maneuverability of the aircraft, and also conflict management support systems, including aviation, navigation and communication systems. Communicate with PF, and initiate contact with ATCo to report any significant failures if needed, with the purpose of updating ATCo's SA on flight systems' limitations and for receiving feedback on further course of actions.
Remarks:	None.
	Concluded

Table 4.29: PNF's task cluster PNF_{ii}: **Stall Recovery**

Cluster:	**Stall Recovery**
Tasks Included	**AVI**: B1, C2, C3, C4, C5, C7
Relates to:	Insufficient or late detection of loss of airspeed. Both the PF and PNF have failed in detecting the airspeed loss earlier. The aircraft has lost its speed to a point beyond the minimal operating speed, where the occurrence of stall condition is considered irreversible. The stick shaker is activated next.
Includes:	Notice the activation of the stick shaker. Observe the insufficient airspeed, and understand the imminent stall condition. Communicate with PF and raise awareness of the problem at hand, if communication is not initiated by PF. Decide on the execution of a stall recovery procedure as the appropriate solution, if not acted upon by the PF. Monitor the execution of corrective actions and the event sequence applicable to the stall recovery. Check if the aircraft has acquired appropriate airspeed after execution of the resolution tasks.
Remarks:	1. The aircraft, at this point, is already beyond the critical stall speed, and will stall to the ground if no corrective actions are taken by the flight crew. The PF is considered as the pilot in charge of flying the jet, and as such, the PF is assumed to execute the stall recovery procedure. The PNF will thus not be required to make a decision on and execute the stall recovery. The PNF is, however, still responsible for the monitoring of the execution of the stall recovery procedure. This will include a monitoring of PF's proper execution of stall-related duties.
	Continued on next page

Continuation of Table 4.29

Cluster:	**Stall Recovery**
	The distribution of tasks in between the flight crew is assumed to have been established beforehand, either under airline guidelines, or during flight plan preparations. As such, the PNF shall act as a monitoring body while the PF acts as the pilot responsible for executing critical resolution actions.
	Concluded

Table 4.30: PNF's task cluster PNF_{iii}: **Speed Conflict Resolution Monitoring**

Cluster:	**Speed Conflict Resolution Monitoring**
Tasks Included	**AVI**: B1, C2, C3, C4, C5, C7
Relates to:	The aircraft is flying significantly slower than the intended airspeed, and visual warnings have emerged on PNF's PFD screen. The aircraft is not yet in a definite stall condition, and the stick shaker has not yet been activated.
Includes:	Notice the PFD's visual alerts regarding the low airspeed. Comprehend the conflict and understand the dangerously low airspeed. Communicate with PF over the potential formation of stall, and create potential solutions. Monitor execution of corrective tasks and event sequence. Check if the flight is safe and if the alerts are eliminated after execution of the resolution tasks.
Remarks:	1. The aircraft, at this point, is not yet in a critical condition and the minimum airspeed (stall airspeed) has not yet been reached. 2. The distribution of tasks has been established beforehand. As such, the PNF shall act as a monitoring body. 3. The monitoring responsibilities of the PNF shall include the monitoring of PF's proper execution of corrective actions. The PNF may and should challenge the PF if necessary, to avoid or correct for an incomplete conflict resolution.
	Concluded

Table 4.31: PNF's task cluster PNF_{iv}: **Sensor Failure Resolution Monitoring**

Cluster:	**Sensor Failure Resolution Monitoring**
Tasks Included	**AVI**: C1, C2, C3, C4, C5, C7
Relates to:	Inconsistencies in LRRA's outputs detected.
Includes:	Understand that the altitude indications are not reliable, and communicate with PF over the conflict.
	Continued on next page

Continuation of Table 4.31

Cluster:	**Sensor Failure Resolution Monitoring**
	Understand the link to a potentially faulty LRRA. Also assess and realize the flight system to be potentially affected as a result of the wrong RA feedback. This shall include the realization of the risks towards an affected A/T. Maintain full coordination with PF, create potential solutions and decide on execution of the most appropriate resolution tasks. Monitor the execution of the corrective tasks, and provide back-up to the PF, if requested. Check if the flight is safe, and keep an eye for further possible alerts.
Remarks:	The PNF remains responsible for monitoring the resolution tasks and also the PF's performance.
	Concluded

Table 4.32: PNF's task cluster PNF_v: **Go-Around**

Cluster:	**Go-Around**
Tasks Included	**NAV**: A2, C2, C3, C4, A5, B5
Relates to:	Failure of crew in achieving a stabilized approach upon reaching 1,000 ft, causing the need to avoid the approach and perform a go-around.
Includes:	Examine the completion of the approach checklist. Understand the current approach phase, take note of the altitude over the runway, and understand the non-stabilized status of the approach. Communicate with PF to increase awareness regarding the situation and the need for an immediate go-around. Detect and inform PF if there are strong reasons why a go-around cannot be completed. However, if a go-around is confirmed, initiate contact with ATCo and discuss the situation.
Remarks:	1. Full execution of a go-around is not included in the modeling. As such, PNF's future tasks of monitoring the go-around shall be neglected. 2. Since the execution of a go-around is beyond the scope of this modeling, the occurrence of additional difficulties during a go-around procedure are not included here.
	Concluded

Table 4.33: PNF's task cluster PNF_{vi}: **Emergency Actions**

Cluster:	**Emergency Actions**
Tasks Included	**AVI**: A10, B10, **NAV**: A10, B10, **COM**: A9, C10, **MIS**
Relates to:	The situation in which the main controlling functions cannot be completed, due to significant on-board component failures.
Includes:	Take notice of any abnormality or malfunctioning of system controls. Communicate with PF and raise awareness. Realize the resulting limitations in functionality of the aircraft. Review the regulations and emergency procedures, and consult with ATCo. Gather information regarding the procedures to be followed in order to tackle the issue. Inform the PF, if he or she remains unaware. Ensure that the emergency actions are properly understood and conducted by the PF at full attention. Challenge, warn and correct the PF, if needed. Fulfill the remainder of tasks as PNF.
Remarks:	None.
	Concluded

Table 4.34: PNF's task cluster PNF_{vii}: **Air-Ground Communications**

Cluster:	**Air-Ground Communications**
Tasks Included	**AVI**: C9, A10, B10, **NAV**: A10, B10, **COM**: C10, **MIS**
Relates to:	The communications between the cockpit crew and the ground controller.
Includes:	Throughout the flight, respond to ATCo's incoming messages and initiate and maintain sufficient communication with ATCo, whenever applicable. This includes receiving and responding to ATCo's instructions regarding the STAR and other clearances, and upon detection of system failures, difficult conditions or other unknown problems.
Remarks:	PNF carries full responsibility for air-ground communications at all time, unless PF decides to back-up the PNF or is forced to step in.

Table 4.35: PNF's task cluster PNF_{viii}: **Miscellaneous**

Cluster:	**Miscellaneous**
Tasks Included	**AVI**: C9, A10, B10, **NAV**: A10, B10, **COM**: C10, **MIS**
Relates to:	The remainder of the tasks applicable to the PNF, not yet covered under the previous clusters.
Includes:	Ensure a proper and sufficient execution of tasks related to aviation, navigation and communication is possible. Detect failure of own system components, and report to ATCo.
Remarks:	None.
	Concluded

4.2.11. EXECUTION OF TASKS ACCORDING TO CONTROL MODES

Throughout Sections 4.2.1 to 4.2.10, the tasks applicable to PF and PNF have been identified, detailed, and mapped into appropriate clusters. This section provides a recap of these task clusters, and using the Contextual Control theory of Hollnagel (Hollnagel, 1993), models the behavior of the pilots under different control modes. This will help understand how the behavior and performance rate of the crew would differ, given the different mode they would be operating at, thus outlining the performance differences at normal and abnormal conditions.

A priority hierarchy is applied to indicate the tasks in the order of their priorities. The priority is simply for the purpose of distinguishing between more critical tasks, and those where the crew has more time and information available before making a decision. A fully developed conflict is deemed as most critical, since the crew is provided with a significantly smaller time window to react, and less information is available to them while they are struggling to save the aircraft from imminent danger. The conditions leading up to a fully developed conflict are considered next, followed by overall task clusters to be performed throughout the flight.

RECAP AND MODELING OF PF'S TASK CLUSTERS

A recap of PF's task clusters during the operation considered is given below. As it can be seen, the clusters have been reordered to represent a prioritization based on the status of the conflict.

PF_i:	Conflict Sensing
PF_{ii}:	Stall Recovery
PF_{vii}:	Emergency Actions
PF_{iii}:	Sensor Failure Resolution
PF_{iv}:	Go-Around
PF_v:	Speed Conflict Resolution
PF_{viii}:	Miscellaneous

As it was described in Section 4.2.9, the task cluster PF_{vi} 'Back-up the PNF' is omitted from the above list of PF's task clusters.

Next, per each task cluster, PF's possible deviations in behavior and performance are outlined. For this purpose, the following two control modes of Hollnagel's Contextual Control theory will be applied. Compared to Chapter 4.1.1, a more detailed description of the two modes is given below:

- **Opportunistic** mode
  Under an opportunistic control mode, the choice of the forthcoming action is based on the current context. No or very limited planning is performed ahead of choosing an action. This can be a result of an insufficient time available for making a decision or due to improper understanding of the context.
  Often, multiple inefficient and pointless attempts are made following an opportunistic mode of control.

- **Tactical** mode
  In a tactical control mode, the operator does not yet have a time horizon as wide as the Strategic mode. However, he or she can enjoy from a time horizon beyond the dominant needs of the present. In order to choose the next line of action, the operator follows a known procedure or rule. The planning, however, remains of limited scope, influenced by ad hoc needs at times.

The elaborations are provided in Tables 4.36 to 4.42.

Table 4.36: Modeling of PF's performance; task cluster PF_i, **Conflict Sensing**

Control Mode	Task Cluster: **Conflict Sensing**
Opportunistic	The PF notices the automated alerts as they come in; however, he may sometimes fail to spot visual alerts. A stick shaker will never be missed by the PF. The landing gear warning will be observed by the PF, however, the PF may simply ignore the warning having noticed the irrelevance of the warning to the current flight altitude. There will thus be little to no assessment of the reasoning behind the warning, and as such the conflict may not be thoroughly understood.

Continued on next page

Continuation of Table 4.36

Control Mode	Task Cluster: **Conflict Sensing**
	Low airspeed, inconsistent LRRAs' RA readings, and the unstable approach may be missed.
Tactical	The PF notices the automated alerts as they come in. Upon detection of a warning, either visual or aural, the PF considers the applicability of the warning, and if necessary, proceeds to discuss the warning with the PNF. Although no warning will be ignored under a tactical mode, there can still be no guarantee that the PF will prioritize the comprehension of a warning over the remainder of his or her tasks, and as such full discussion of all generated warnings can not be guaranteed.
	Concluded

Table 4.37: Modeling of PF's performance; task cluster PF_{ii}, **Stall Recovery**

Control Mode	Task Cluster: **Stall Recovery**
Opportunistic	Having detected the stick shaker warning, the PF realizes the stall condition. The PF may or may not discuss the conflict and the appropriate solution with the PNF. A response to the conflict in the form of a stall recovery procedure is immediately initiated, possibly without any assessment of aircraft's maneuverability or a consideration of any other undetected failure. Although the PF might have achieved a correct understanding of a faulty LRRA-1, he or she may fail to realize or to remember the need for disengaging the A/T. As such, the PF's resolution task may be doomed to failure, since the A/T will not be capable of processing the PF's inputs to increase the airspeed.
Tactical	Having detected the stick shaker, the PF realizes the stall condition, and communicates the conflict with the PNF. The need for the execution of the stall recovery is briefly communicated, followed by the execution of the recovery solution by the PF. Benefiting from a wider time horizon, and the ability to base the decisions on a wider range of information, the PF will be capable of realizing the need for the disconnection of the A/T. As such, the increase of the airspeed is manually implemented, as part of the stall recovery procedure. The PF will eventually check if the conflict is resolved and if appropriate airspeed has been achieved.
	Concluded

Table 4.38: Modeling of PF's performance; task cluster PF_{vii}, **Emergency Actions**

Control Mode	Task Cluster: **Emergency Actions**
Opportunistic	The PF reacts to the conflict through relying on his immediate understanding of the situation. In order to make a decision, the PNF uses the indications immediately available to him or her on the cockpit screens. There may or may not be a communication inside the cockpit initiated by the PF, lowering the chance of a coordinated understanding of appropriate course of action. Following the lack of sufficient time available and the ad hoc-type situation inside the cockpit, the PF shall not proceed to consider the emergency procedures and will base the decision on the immediate recovery of the aircraft.
Tactical	The PF reacts to the conflict through communicating the emergency, the relative warnings and the limitations detected in maneuverability of the aircraft with the PNF. Having increased the crew's SA of the conflict at hand, the PF consults relevant emergency procedures, and requests or initiates contact with the ATCo for more feedback. Next, a decision is made and executed.
	Concluded

Table 4.39: Modeling of PF's performance; task cluster PF_v, **Speed Conflict Resolution**

Control Mode	Task Cluster: **Speed Conflict Resolution**
Opportunistic	Having observed the visual alerts on the PFD related to the airspeed, the PF understands the conflict of a low airspeed, and proceeds to resolve the issue. This will include PF's direct attempt at increasing the generated thrust of the engines or a pitch down movement if applicable, and as such, increasing the airspeed of the aircraft. The PF will make no reference to the flight plan, or the clearance given by the ATCo. Given the limited reaction time, the PF will directly issue an increase in airspeed to keep the aircraft away from a near-stall airspeed. The PF may or may not discuss the conflict with PNF before executing the resolution action. As such, the conflict priority, and any related malfunctioning may or may not be assessed. The conflict is resolved. However, the airspeed increase may be in excess of what is required with regards to the flight status or flight plan. The PF may or may not check the execution of the maneuvers and the event sequence in the meantime.
	Continued on next page

Continuation of Table 4.39

Control Mode	Task Cluster: **Speed Conflict Resolution**
	It should be realized that the execution of the entire task cluster PF_v is dependent on the outcome of PF's task cluster PF_i, in which the PF may also fail to detect the visual warnings.
Tactical	Having observed the visual alerts on the PFD related to the airspeed, the PF investigates the actual airspeed the aircraft is flying at, while confirming the intended airspeed with the PNF. The PF realizes the speed conflict, discusses the matter with PNF, and gets an updated SA with regards to the conflict priority and the margin of current airspeed from the stall region. The PF achieves a correct understanding of the requirements in terms of airspeed increase, and proceeds to implement the solution through adjusting engine settings or the aircraft attitude. PF monitors the procedure while the aircraft gains airspeed, and checks if the conflict is resolved.
	Concluded

Table 4.40: Modeling of PF's performance; task cluster PF_{iii}, **Sensor Failure Resolution**

Control Mode	Task Cluster: **Sensor Failure Resolution**
Opportunistic	Having observed the inconsistencies between altitude readings on the PFD's, the PF realizes that there is a significant difference between the two outputs, but may or may not realize the actual severity of the conflict. Since no immediate danger is yet predicted, and no alerts are generated, PF might even assume that the inconsistency is temporarily, and decide to delay the investigation to a later moment. The PF may or may not proceed to discuss the matter with PNF, limiting the chance for the crew to properly relate the conflict to a faulty altimeter. As a consequence, the PF will not investigate the potential cause and most importantly, the avionics components to be possibly affected by the malfunctioning will not be identified. Without a thorough analysis of the condition, the PF will not gain a sufficient update of own SA to be capable of reasoning a need for disengaging the A/T.
Tactical	Having observed the inconsistencies between altitude readings on the PFD's, PF discusses the matter with PNF and raises awareness with regards to the erroneous and unreliable altitude data. PF will next be able to link the faulty altitude data to a faulty altimeter.
	Continued on next page

Continuation of Table 4.40

Control Mode	Task Cluster: **Sensor Failure Resolution**
	The PF considers potential consequences of a faulty LRRA, and may succeed in establishing the link between the faulty LRRA and the A/T. Upon a successful recognition of the conflict, PF disengages the A/T and the A/P, and continues a manual flight. The decision is communicated to the PNF, as well. The PF, however, may also fail in understanding the direct influence of a malfunctioning LRRA-1 on the A/T. This is considered as feasible, since there is no direct source of information available to the crew to warn them of such possibilities.
	Concluded

Table 4.41: Modeling of PF's performance; task cluster PF_{iv}, **Go-Around**

Control Mode	Task Cluster: **Go-Around**
Opportunistic	The PF follows the safety regulations and as such, aborts the approach and executes a go-around. The PF will base his or her decision solely on own understanding of the condition and of the requirements following such conditions. The PF does not include the PNF in the decision making process. The PF may or may not communicate the final decision with the PNF. Following the lack of sufficient time available to the PF for decision making, he or she may fail to check whether the go-around is practical and conflict-free on the short term. For instance, he may fail to consider factors such as environmental issues.
Tactical	Through communication with the PNF, and based on own knowledge regarding the regulations, the PF comes to the conclusion that the regulations would require an abortion of the approach and an execution of a go-around. The PF thus builds up knowledge of the conflict priority. Regardless of the regulations, the PF will proceed to analyze the situation and assess if a go-around is practically possible. Factors such as lack of fuel, or environmental factors may be included in the decision making. The PNF is kept informed throughout the decision making. If considered unsafe, the PF decides on the continuation of the approach, and shares the decision with the PNF. Otherwise, PF obeys the regulations and confirms the execution of a go-around. The decision is shared with PNF, requesting the PNF to initiate contact with ATCo and notifying the controller of the decision.
	Concluded

Table 4.42: Modeling of PF's performance; task cluster PF_{viii}, **Miscellaneous**

Control Mode	Task Cluster: **Miscellaneous**
Opportunistic	PF detects majority of failures of the aircraft components. However, he or she might fail to detect some others, or might forget some of those which were detected earlier. If PF fails to detect or remember any critical error, his or her SA of the overall functionality of the aircraft will remain incomplete, preventing the PF from planning and performing corrective actions in time.
Tactical	Overall, the PF pays proper attention to ensuring his or her tasks are executed sufficiently. Although at times, some tasks may not be fully executed, PF does sufficient in incorporating regulations, own knowledge and assessment of available information prior to any decision making. PF detects, remembers and communicates failures of aircraft components with the PNF.
	Concluded

RECAP AND MODELING OF PNF'S TASK CLUSTERS

The PNF's task clusters are next recapped and modeled in the order given below. The performance of the PNF is modeled under the same control modes for which the PF's performance was studied.

PNF_i: Failure Sensing
PNF_{ii}: Stall Recovery
PNF_{vi}: Emergency Actions
PNF_{iii}: Speed Conflict Resolution Monitoring
PNF_{iv}: Sensor Failure Resolution Monitoring
PNF_v: Go-Around Monitoring
PNF_{vii}: Air-Ground Communications
PNF_{viii}: Miscellaneous

Table 4.43: Modeling of PNF's performance; task cluster PNF_i, **Failure Sensing**

Control Mode	Task Cluster: **Failure Sensing**
Opportunistic	The PNF might fail to detect some failures. Out of those detected, PNF does not communicate all failures to the PF. The PNF might decide to momentarily store the information regarding the failure of some components at short term memory, with the intention of further assessment before reporting to the PF. However, he or she might be distracted by newly identified tasks.
	Continued on next page

Continuation of Table 4.43

Control Mode	Task Cluster: **Failure Sensing**
	The PNF might fail in initiating contact with ATCo when required, preventing ATCo from providing any assistance.
Tactical	The PNF notices the warnings, visual and aural, and detects the failures of the corresponding components. Proceeds to communicate the failure with PF, to ensure the crew achieves a balanced SA. PNF contacts the ATCo on time, if further feedback is required.
	Concluded

Table 4.44: Modeling of PNF's performance; task cluster PNF_{ii}, **Stall Recovery**

Control Mode	Task Cluster: **Stall Recovery**
Opportunistic	The PNF notices the stick shaker and immediately recognizes the insufficient airspeed. The communication between the PNF and the PF, if any, will only be in the form of a single statement stating the stall condition. The PNF fails in discussing the cause, the execution of the solution or any other relevant procedure with the PF. The PNF will only challenge the PF if he or she does not reach out for an increase in the generated thrust. The PNF is only focused on immediately achieving an increasing pattern in the value of airspeed indicated on the PFD.
Tactical	The PNF notices the activation of the stick shaker warning, and understands the insufficient airspeed of the aircraft. The PNF communicates the situation with PF, and coordinates with him or her the stall recovery procedure. While the PF executes the recovery procedure, the PNF monitors the process and warns the PF if he or she fails to properly increase the generated thrust to the possible maximum range. PNF checks the event sequence of the procedure and confirms if the aircraft has gained sufficient safety margin from a stall region. In the meantime, the PNF attempts to monitor the remainder of flight parameters as well.
	Concluded

Table 4.45: Modeling of PNF's performance; task cluster PNF_{vi}, **Emergency Actions**

Control Mode	Task Cluster: **Emergency Actions**
Opportunistic	PNF may or may not fully communicate his or her findings of the conflict with PF. Takes note of the relative emergency procedures and acts accordingly. The decision is mostly based on generated alerts and intuition. As such, with no communication with PF, the decision may not be sufficient. May or May not challenge the PF in the event of incorrect actions.
Tactical	PNF notices the flight difficulty, communicates with PF to raise awareness and to possibly locate the corresponding cause. Takes note of the relative emergency procedures and assists the PF in consulting the emergency procedures. Continues to monitor the procedure and will challenge the PF if needed. Will contact the ATCo, if considered necessary or if requested by ATCo, and continues to complete own monitoring responsibilities.
	Concluded

Table 4.46: Modeling of PNF's performance; task cluster PNF_{iii}, **Speed Conflict Resolution Monitoring**

Control Mode	Task Cluster: **Speed Conflict Resolution Monitoring**
Opportunistic	PNF detects visual warnings on own PFD. However, he or she may also fail to detect the warnings. As such, the PNF may or may not communicate with and alert the PF on time. IF warnings are detected, PNF discusses a solution with PF. The final solution is purely based on avoiding a stall and results in a direct increase in airspeed. An excessive increase in airspeed might also be achieved. PNF does not monitor the execution of corrective actions, and is only concerned about achieving an increase in airspeed.
Tactical	PNF detects the visual warnings on own PFD. He or she communicates the warnings with PF, raising the awareness regarding the loss of airspeed. Next, PNF coordinates with PF a solution in the form of increasing the airspeed. The decision is based on an assessment of actual speed the aircraft is flying at, and the target airspeed. PNF may challenge the PF if the increase in airspeed is not achieved sufficiently and quickly. PNF monitors the resolution actions and the corresponding event sequence, and checks if the warnings are omitted.
	Concluded

Table 4.47: Modeling of PNF's performance; task cluster PNF_{iv}, **Sensor Failure Resolution Monitoring**

Control Mode	Task Cluster: **Sensor Failure Resolution Monitoring**
Opportunistic	Following the aural landing gear warning, PNF may or may not detect the inconsistencies in LRRA outputs. PNF's understanding of the LRRA inconsistencies also depends on PF's performance and communication about LRRA-1 output. Thus, may or may not discuss the inconsistencies with the PF. If PF and PNF both do not discuss the inconsistencies, the SA will not be upgraded. As such, the crew will not become aware of the arising conflict, and will not proceed to link it to the potential misbehavior of the A/T. In the event the inconsistencies are picked up, PNF may still fail in successfully linking the failure of LRRA-1 to the A/T, making it very unlikely for the PNF to contribute in encouraging the PF to issue a manual flight.
Tactical	Having detected the aural landing gear warning, PNF proceeds to study the actual flight altitude, communicates with PF and detects mismatching outputs of altitude on the two PFD's. Crew's SA of an unreliable LRRA system is balanced next through PNF's communication with PF. PNF investigates the flight manual, to consider potential consequences of LRRA failure, after which the team might decide on a manual flight given the uncertainties of their flight equipment.
	Concluded

A number of remarks should be mentioned over PF's and PNF's execution of their tasks regarding the resolution of a sensor failure conflict. Given the crew's successful detection of the inconsistencies in between the two LRRA outputs, as discussed in Tables 4.40 and 4.47, the necessary information to warn the crew of a direct influence of a faulty LRRA-1 output on the A/T is not directly available. Hidden deep within the design structure of the avionics, neither of the flight manuals, training or crew's intuition would have allowed for the crew to directly link the conflict to a failure of the A/T.

The decision of the crew of the previous flights to disengage the A/T upon detection of a faulty RA-1, would have been considered as protective measures against the uncertainties of their flight equipment. As such, the decision could not have been based on a direct feedback of any available guidelines or manuals (Dutch Safety Board, 2010). The condition worsens when the crew considers the failure of LRRA-1 exclusive to the single component. This may lead to the crew's decision on ignoring the LRRA-1 output, which will result in their failure in checking for any additional LRRA-related failures.

Table 4.48: Modeling of PNF's performance; task cluster PNF_v, **Go-Around Monitoring**

Control Mode	Task Cluster: **Go-Around Monitoring**
Opportunistic	Flying an unstable approach upon reaching 1,000 ft, PNF may or may not realize the requirement for a go-around. This may result from an extensive task responsibility or lack of attention to the guidelines. As such, with a low probability of the PNF warning the PF, it will be up to the PF to recognize the unstable approach and consider the need for a go-around. On the other hand, if detected by PNF, he or she follows the procedure and directly instructs the PF on a need to execute a go-around. The PNF will not consider the possibility to continue the approach as it is. The decision is based on PNF's intuition to follow the requirements. The PNF will not object to PF's possible decision on continuation of the approach. Overwhelmed with the situation, PNF fails to communicate the late stabilization to the ATCo, should the crew decide on continuing the approach.
Tactical	PNF realizes that the approach is not stabilized by the time the altitude of 1,000 ft is achieved. PNF uses own knowledge from training, if available, to warn PF that a go-around should be executed, if not already communicated by the PF. PNF builds up knowledge of conflict priority, along with current status of aircraft components such as the available fuel, in order to assess if a go-around can be safely executed. Warns the PF in the event of potential complications. If a go-around is concluded, PNF communicates it to ATCo and requires a new flight route and approach.
	Concluded

Table 4.49: Modeling of PNF's performance; task cluster PNF_{vii}, **Air-Ground Communications**

Control Mode	Task Cluster: **Air-Ground Communications**
Opportunistic	PNF is distracted with additional tasks, or the magnitude of the issue at hand, and as such may fail in communicating potential conflicts with the ATCo in a timely manner.
Tactical	In the event of difficult conflicts, PNF initiates contact with ATCo at proper timing in order to receive feedback on further course of actions. This also bears the objective of informing the ATCo of possible landing priorities for the flight.
	Concluded

Table 4.50: Modeling of PNF's performance; task cluster PNF_{viii}, **Miscellaneous**

Control Mode	Task Cluster: **Miscellaneous**
Opportunistic	PNF may fail in detecting failure of other aircraft components. Out of those detected, PNF might forget some which were detected earlier, or might wrongly predict their relative conflict priorities. This may result in PNF's incomplete understanding and execution of own responsibilities.
Tactical	PNF pays sufficient attention to monitoring and executing own responsibilities. PNF detects, remembers, and communicates failures of aircraft components to the PF.
	Concluded

4.3. ASSESSMENT OF CREW'S COGNITIVE PERFORMANCE VARIATIONS

Section 4.2.11 provided the possible variations in crew's cognitive performance, given the different control modes of operation. One can now use these findings to analyze the crew's cognitive performance ability in detection, management and resolution of a potential conflict. It should, however, be realized that the objective of the modeling in this chapter is to provide a better understanding of the possible variations in the performance rate of the crew given the control mode they would be operating at. For a quantitative accident risk assessment of a similar operation, the reader is referred to Chapter 5.

Given the abnormal flight conditions following the malfunctioning of the left radio altimeter, the LRRA-1, the tasks clusters broke the crew's responsibilities down into specific categories of tasks to be executed. Next, the application of the control modes outlined the differences in performance given the specific mode the pilot would be operating at. The differences in performance observed in the application of the Contextual Control theory are discussed here under four main performance-related components, outlined here.

4.3.1. DETECTION AND REALIZATION OF CONFLICT DEVELOPMENT

A clear similarity in between the two crew members would be related to the failure of the crew members in detecting all related warnings and thus failures should an abnormal and unsafe condition arise while the crew are acting in an opportunistic mode. Depending on the definition of the boundary separating the two opportunistic and tactical modes, the crew will significantly lose their abilities to focus and properly monitor their equipment and detect warnings indicated on their screens, as they enter the region of an opportunistic control mode. Detailed in Tables 4.36 and 4.43, an opportunistic-modeled pilot will be vulnerable to incomplete monitoring of the cockpit screens, and detection and comprehension of the generated warnings.

In addition, the 'visual' format of the warnings related to the loss in altitude and airspeed contribute to the higher probability of a warning to be missed by a stressed or highly occupied crew member. Given the scenario in which the crew have not detected the 'Retard-Flare' mode of their A/T on time and are as a result losing airspeed, the crew will only be supported by aural warnings when the hazardous conflict is already partially developed. Aural warnings have the benefit of an external attention-seeker noise projected to the crew, with a higher probability of being detected, compared to the visual warnings on the PFD's. It should, however, be realized that an opportunistic-modeled pilot may still fail in taking an observed aural warning into serious consideration, given the stress or overwhelmed condition of the pilot. There remains thus no quarantine for an opportunistic-modeled pilot to fully execute his or her responsibilities of continuous monitoring and conflict sensing.

4.3.2. Communication

For an opportunistic-modeled operator, where the pilot has a smaller probability to detect and understand the formation of an abnormal and unsafe event, the opportunity to be informed by the other crew member or by an external operator such as the ATCo will be highly essential to make sure the pilot can react accordingly and in time. However, the presence of the two crew members in an opportunistic mode would ultimately create the situation in which no information is communicated in between the two crew members. In addition, the current ATC surveillance system does not allow the ATCo full accessibility and monitoring of all occurrences on all flights, and as such limits the line of feedback initiated by the ATCo upon his or her observation of abnormal conditions on a specific flight. As such, with no inner- or external communications, the crew will remained uninformed of the occurrence of any failure and unaware of the associated development of a hazardous and unsafe situation.

This was clearly experienced on the approach of Flight TK1951, through which no communication was made in various phases of the flight concerning the failure or incorrect status of the avionics systems aboard the flight. The data available of the communications made on-board Flight TK1951 is presented in Appendix B. As it can be seen from the actual communications in between the crew, the crew failed to fully communicate the occurrences throughout the flight. In regards to the task clusters, it can be obtained from the data of Appendix B that communication-related tasks of clusters related to sensing of the conflict, in addition to conflict management, preparation and execution of corrective solutions were not sufficiently performed. In order for a better and quantitative link between the control mode of the flight crew and the insufficient level of communications on Flight TK1951, the reader is advised to study the simulations performed in Chapter 5.

4.3.3. PNF's contribution to Conflict Management

While a PNF is intended to lower the workload of the PF by performing tasks such as communication with ATCo and adjustment of aircraft's mechanical control surfaces, a primary responsibility of the PNF relates to monitoring of cockpit instruments and assisting the pilot in detecting any abnormal flight conditions.

However, obtainable from Tables 4.43 to 4.50, it can be concluded from the performance of an opportunistic-modeled PNF that, compared to a tactical-modeled PNF, the PNF acting in an opportunistic mode is likely to fail significantly in performing his or her tasks in supporting the PF. An under-performing PNF directly affects the performance of the PF, jeopardizing the performance of the PF regardless of the control mode he or she is acting at. With less information communicated by the PNF to the PF, the PF will be solely responsible for the detection and comprehension of all occurrences around the flight crew, and will have to base the decisions on his or her own intuition and own SA, no matter how updated the SA is. The PNF, with an incomplete SA of the conflict, will be unable to properly assist in decision makings and will not be confident or will do insufficiently in challenging and correcting the decisions made by a more informed PF.

4.3.4. CONFLICT MANAGEMENT AND RESOLUTION

The task clusters defined for either of the two crew members introduced multiple conflicts that need recognition, management and resolution by the crew members. The ability of each crew member to correctly plan and execute resolution actions may be significantly jeopardized as a result of an insufficient control mode. As it was detailed per task cluster in Section 4.2.11, the two executive and monitoring pilots are both subjected to serious performance limitations while acting in an opportunistic mode. Responsible for constructing potential solutions and selecting the most appropriate solution using all information available, an opportunistic-modeled PF is vulnerable to making ad-hoc assessments of the situation, and as such, may implement incomplete or excessive means of correction. On the side of the cockpit, an opportunistic-modeled PNF may easily be overwhelmed with the magnitude of the conflict, fail to consider relative safety regulations and to warn the PF accordingly, or act purely on intuition and based on what he or she perceives of the situation at the moment. In addition, the PNF will most likely not reach out to the ATCo for supportive feedback, due to lack of time and distraction with the sudden appearance of the conflict.

The crew's chain of failures in detection, recognition and resolution of the conflicts will eventually lead to the situation, in which a reasonably non-critical malfunctioning may cause an event sequence through which a serious and unrecoverable system failure may bring down the aircraft. As such, the importance of the control mode to which the crew's performance at the critical moments of the flight can be coupled becomes evident. In order to link the above observations of crew's cognitive performance modeling with a quantitative assessment of the operation risk, Chapter 5 will next provide a quantitative modeling of the operation, on the basis of the event sequence of Flight TK1951, described in this chapter.

5

SIMULATIONS

Chapter 4 established a qualitative assessment of the influence of a jeopardized crew's performance on the overall outcome of the operation. This chapter conducts a number of quantitative assessments with the aim to further examine the behavior of PF and the on-board and external factors affecting the pilot's performance. An assessment of the rate of safety of the actual event sequence of Flight TK1951 is conducted first, which also sets up the reference event sequence based on the actual occurrences of Flight TK1951. Next, different variations of the reference flight scenario are studied and simulated. As such, one will be able to compare the corresponding outcomes, and draw a more informed conclusion on the formation and contributing factors of the crash landing of Flight TK1951.

The chapter starts with a description of tasks applicable to each crew member during the approach, shown in Section 5.1, building up the event sequence of the reference flight. Section 5.2 will next establish the magnitude of the PF's taskload vector throughout the flight, as he or she attempts to tackle all relevant tasks. This is followed by the introduction and computation of a success likelihood probability of the operation in Section 5.3, based on the taskload vector established earlier. In order to analyze the degree of influence of on-board system failures and external factors on the outcome of the operation, Section 5.4 analyzes the success likelihood probability for various variations of the reference operation. The chapter is concluded with an analysis of the findings, presented in Section 5.5.

Since the captain, occupying the left seat of the cockpit is considered as the active PF, only PF's tasks are further simulated. The contributions and support available from the PNF will still be included.

5.1. REFERENCE EVENT SEQUENCE

In order to construct the simulations, one will have to establish the task list of the flight crew members relevant to the final approach of the flight. For this purpose, Paassen's paper on the analysis of pilot task activities relevant to a final approach is used (Paassen, 1986). Using the default composition of a two-seated cockpit, Paassen distinguishes between tasks relevant to each of the crew members. Paassen's identification of crew's tasks is incorporated as the basic framework of the operation. Combined with the official investigation report of Flight TK1951 (Dutch Safety Board, 2010), this provides the reference event sequence of an approaching flight, based on the flight conditions of Flight TK1951.

Next, the tasks associated to the PF and PNF are extracted from the established reference event sequence. For the purpose of defining the tasks of PF and PNF, the time at which each task becomes known to the relevant pilot and the duration of the task, dt, are noted. In addition, per task, the corresponding trigger that alerts the pilot of the need to execute the task is identified, along with an indication of an external trigger, if applicable. Tables 5.1 and 5.2 present the tasks associated to the PF and PNF during the reference flight scenario, respectively.

Table 5.1: Tasks applicable to PF during the reference flight scenario

Task #	**Time [s]**	**Trigger**	**Task**	**dt [s]**	**Ex. Tr.**
1	0	Time = 0 *seconds*	Crew Briefing	20	
2	20	Briefing completed	Request landing checklist	2	
3	62	Incoming ATC message(1) Updates crew over instructions to: - Decelerate to 220 *knots*, - Turn left to heading 265 *degrees*, - Descent and hold 2,000 *ft* to intercept localizer, - Target runway heading of 180 *degrees*	Decode ATC message(1)	1	x
4		ATC message(1) decoded	Process ATC message(1) Trim to turn; select 265 *degrees* on MCP	2	x
5		ATC message(1) decoded	Process ATC message(1) Trim to decelerate; select 220 *knots* on MCP	2	x
6		ATC message(1) decoded	Process ATC message(1)	2	x

Continued on next page

Continuation of Table 5.1

Task #	Time [s]	Trigger	Task	dt [s]	Ex. Tr.
			Trim to descent; select 2,000 ft on MCP		
7	719	Aural Landing gear warning generated	Notice the warning	2	x
8		Landing gear warning noticed	Communicate with PNF on potential cause	4	
9		Communicated with PNF on potential cause	Realize faulty RA-1, and Update SA{malfunctioning LRRA-1, causes and consequences}	2	
10 **11** **12**	731	Trigger(7) Trigger(8) Trigger(9)	Task(7) Task(8) Task(9)	2 4 2	x
13 **14** **15**	844	Trigger(7) Trigger(8) Trigger(9)	Task(7) Task(8) Task(9)	2 4 2	x
16 **17** **18**	952	Trigger(7) Trigger(8) Trigger(9)	Task(7) Task(8) Task(9)	2 4 2	x
19	1133	Target altitude of 2,000 ft reached	Observe and Update SA{Trim to descent completed}	1	
20	1150	Target velocity of 220 $knots$ reached	Observe and Update SA{Trim to decelerate completed}	1	x
21		Updated SA{Trim to decelerate completed}	Request Flaps 1	2	x
22		PNF confirms Flaps 1	Trim to decelerate; select 195 $knots$ on MCP	2	x
23	1171	ATC message(2) Updates crew over instructions to: - Turn left to heading 210 $degrees$ to intercept	Decode ATC message(2)	1	x
24		ATC message(2) decoded	Process ATC message(2) Trim to turn; select 210 $degrees$ on MCP	2	x
25	1186	A/P disconnect alert sounded	Detect the warning	2	x
26		A/P disconnect alert detected	Realize A/P's disengaged, Update SA{A/P disconnected}	2	
27		Updated SA{A/P disconnected}	Re-engage A/P-A	4	
28	1190	Target heading of 210 $degrees$ achieved	Enable ILS	2	

Continued on next page

Continuation of Table 5.1

Task #	**Time [s]**	**Trigger**	**Task**	**dt [s]**	**Ex. Tr.**
29	1192	ILS engabled	Enable NAV 1 audio selector	2	
30	1215	NAV-1 enabled	Enable LOC	2	
31	1225	At 195 *knots*	Request Flaps 5	2	x
32		PNF confirms Flaps 5	Trim to decelerate; select 180 *knots* on MCP	2	x
33	1236	Trigger(7)	Task(7)	2	x
34		Trigger(8)	Task(8)	4	
35		Trigger(9)	Task(9)	2	
36	1242	LOC enabled	Enable APP mode	2	
37		LOC and APP enabled	Set auto brake to maximum	2	
38		LOC and APP enabled	Control if speed is between 180 and 220 *knots* for LOC interception, and flaps set at 5 *degrees*	3	
39	1257	PNF calls 'Localizer alive'	Update SA{Localizer alive}	1	x
Localizer Intercepted, at 5.5 *NM* from runway threshold, requiring an interception of G/S from above!					
40	1262	PNF calls 'Localizer captured'	Observe the movement of the F/D command bars with respect to the interception of the G/S	2	x
41		F/D command bars observed	Update SA{G/S to be intercepted from above}	2	x
42		Updated SA{G/S to be intercepted from above}	Communicate with PNF and raise awareness	2	
43		Communicated with PNF on interception of G/S from above	Realize the need for and initiate tasks related to interception of G/S from above. Update SA{tasks for G/S interception}	1	x
44		Updated SA{tasks for G/S interception}	Communicate the tasks with PNF to raise awareness	2	
45		Updated SA{tasks for G/S interception}	Set descent altitude to 1,200 *ft*	3	
46		Descent altitude set to 1,200 *ft*	Set descent altitude to 700 *ft*	3	
47		Updated SA{tasks for G/S interception}	Select V/S mode on MCP	2	
48		Updated SA{tasks for G/S interception}	Set descent rate to 1,400 *ft/min*	4	

Continued on next page

Continuation of Table 5.1

Task #	Time [s]	Trigger	Task	dt [s]	Ex. Tr.
49	1270	LRRA-1 reading of -8 ft shown	Observe erroneous RA-1. Update SA{faulty LRRA-1}	3	
50		Erroneous RA-1 observed	Communicate findings to PNF	2	
51	1276	Localizer intercepted	Request Flaps 15	2	x
52		PNF confirms Flaps 15	Trim to decelerate; select 160 *knots* on MCP for G/S interception	2	x
53		'Retard Flare' mode activated and shown on the PFD	Observe the inappropriate 'Retard Flare' mode of A/T	2	
54		'Retard Flare' mode of A/T observed	Communicate and assess the situation with PNF. Update SA{A/T not controlling airspeed anymore}	3	
55		Updated SA{A/T not controlling airspeed}	Disconnect A/T	2	
56		Updated SA{A/T not controlling airspeed}, and A/T disconnected	Update SA{A/T is disengaged}, Manually adjust throttle lever position	3	
57	1277	ATC message(3) Updates crew over instructions to: - Contact Schiphol tower	Decode ATC message(3)	1	x
58	1278	PNF confirms Flaps 15	Request gear down	2	
59	1299	Target velocity not maintained	Observe the decrease of airspeed below the set target	2	
60		Decrease of airspeed below the set target observed	Update SA{airspeed dropping below target set on MCP, and possible cause}	2	
61	1301	ATC message(4) Updates crew over: - clearance for landing	Decode ATC message(4)	1	x
In the case of a continued landing, at 1,000 ft, PF decides to continue the unstable approach, although regulations require a go-around					
62	1307	At 1,000 ft	PF decides to continue the landing	1	

Continued on next page

Continuation of Table 5.1

Task #	Time [s]	Trigger	Task	dt [s]	Ex. Tr.
63		Decision on continuation of landing	Communicate the decision to continue the landing with PNF	2	
64	1310	Decision on continuation of landing	Request flaps 40	2	
65		A/T disconnected Updated SA{A/T disconnected}, and, PNF confirms Flaps 40	Trim to decelerate; Push throttle levers back for a manual deceleration to 140 $knots$	3	
66		Decision on continuation of landing	Control descent rate manually	3	
67	1350	At 500 ft	Ask the PNF to warn the cabin crew	2	
68	1354	A/T not disconnected, and Amber band shown around the airspeed indicator	Detect the presence of an amber band around the indicated airspeed	2	
69		Amber band detected around the airspeed indicator	Realize the low airspeed	2	
70		Low airspeed realized	Communicate the near-stall airspeed to PNF, and act upon it.	2	
					Concluded

As it can be seen in Table 5.1, the to-be-modeled operation consists of three segments. The first covers the beginning of the operation, in which the malfunctioning of the LRRA-1 could have become known to the flight crew. The possible means for the crew to update their SA of the faulty LRRA-1 include the generation of the landing gear aural warning, and the possibility to extract information from the altitude indications on their PFD's. The second segment of the operation relates to the interception of the localizer signal. Occurring at a distance of 5.5 NM from the runway threshold, the crew is warned and instructed by the F/D function of the FCC to descend and intercept the glide slope signal from above. As such, possible means for the crew to fully update their SA's of the necessary actions to be taken come from the F/D command bars on their PFD's, in addition to the crew's training regarding operation of an ILS landing.

The third and final segment refers to the point at which the aircraft has descended to an altitude of 1,000 ft. With an unstable approach, the crew is left with a decision to execute a go-around, or continue the approach given any safety-concerns making a go-around impossible. Upon the decision of a continuation of the landing, and given the crew's failure in disconnecting the incorrectly fed

A/T, the aircraft will continue losing its airspeed and will eventually enter a stall condition.

It is thus essential for the PF, and the PNF as the supporting and monitoring crew member, to correctly observe and execute their responsibilities throughout all three segments, in order to avoid a formation of a stall condition based on the given event sequence.

Next, the tasks applicable to the PNF are provided in Table 5.2.

Table 5.2: Tasks applicable to PNF during the reference flight scenario

Task #	**Time [s]**	**Trigger**	**Task**	**dt [s]**	**Ex. Tr.**
1	0	PF gives crew briefing	Attend Crew briefing	20	x
2	20	PF requests approach checklist	Perform approach checklist	12	
3	62	Incoming ATC message(1) Updates crew over instructions to: - Decelerate to 220 *knots*, - Turn left to HDG 265 *degrees*, - Descent and hold 2,000 *ft* to intercept localizer, - Target runway heading of 180 *degrees*	Decode ATC message(1)	1	x
4		ATC message(1) decoded	Process ATC message(1); read-back	4	x
5		PF trims the aircraft based on ATC's instructions	Monitor the trimming process, and warn the PF of any wrongdoings	6	
6		ATC message(1) decoded, and having read the message back	Process ATC message(1); set ILS frequency	2	
7	719	Aural Landing gear warning generated	Notice the warning	2	x
8		Landing gear warning noticed by PNF and/or PF	Respond to and communicate with PF on potential cause	4	
9		Communicated with PF on potential cause	Realize faulty RA-1, and, update SA{malfunctioning LRRA-1, causes and consequences}	2	

Continued on next page

Continuation of Table 5.2

Task #	Time [s]	Trigger	Task	dt [s]	Ex. Tr.
10 **11** **12**	731	Trigger(7) Trigger(8) Trigger(9)	Task(7) Task(8) Task(9)	2 4 2	x
13 **14** **15**	844	Trigger(7) Trigger(8) Trigger(9)	Task(7) Task(8) Task(9)	2 4 2	x
16 **17** **18**	952	Trigger(7) Trigger(8) Trigger(9)	Task(7) Task(8) Task(9)	2 4 2	x
19	1133	Target altitude of 2,000 *ft* reached	Monitor and Update SA{Trim to descent completed}	1	
20	1150	Target velocity of 220 *knots* reached	Monitor and Update SA{Trim to decelerate completed}	1	
21		PF requests Flaps 1	Set Flaps 1, check conditions and confirm	4	
22	1171	ATC message(2) Updates crew over instructions to: -Turn left to heading 210 *degrees*	Decode ATC message(2)	1	x
23		ATC message(2) decoded	Process ATC message(2); read-back	4	x
24		PF trims the aircraft based on ATC's instructions	Monitor the trimming process, and warn the PF of any wrongdoings	6	
25	1186	A/P disconnect alert sounded	Detect the warning	2	x
26		A/P disconnect alert detected	Realize A/P is disengaged Update SA{A/P is disconnected}	4	
27		Updated SA{A/P's disconnected}	Warn PF of disconnected A/P, if not noticed by the PF	2	
28	1225	PF requests Flaps 5	Set Flaps 5, check conditions and confirm	4	
29 **30** **31**	1236	Trigger(7) Trigger(8) Trigger(9)	Task(7) Task(8) Task(9)	2 4 2	x
32	1257	Localizer comes alive on PNF's PFD	Call 'localizer alive'	1	x
Localizer Intercepted at 5.5 *NM* from runway threshold, requiring an interception of G/S from above!					

Continued on next page

Continuation of Table 5.2

Task #	Time [s]	Trigger	Task	dt [s]	Ex. Tr.
33	1262	Localizer is intercepted	Call 'localizer captured'	1	x
34		Localizer is intercepted	Observe the movement of the F/D command bars with respect to the interception of the G/S	2	
35		F/D command bars observed	Update SA{G/S to be intercepted from above}	2	
36		Updated SA{G/S to be intercepted from above}	Communicate with PF	2	
37		Communication with PF completed	Update SA{G/S to be intercepted from above}	2	
38		PF sets descent rate to 1,400 ft/min	Monitor the rate-of-descent	4	
39	1270	PF's indication of faulty LRRA	Update SA{malfunctioning LRRA-1}	1	
40	1276	PF requests Flaps 15	Set Flaps 15, check conditions and confirm	4	
41		'Retard Flare' mode of A/T activated and shown on PFD	Observe 'Retard Flare' mode on PFD	2	
42		'Retard Flare' mode of A/T detected	Communicate to PF and assess the situation. Update SA{A/T not in control mode, while it should be}	3	
43	1277	ATC message(3) Updates crew over instructions to: - Contact Schiphol tower	Decode ATC message(3)	1	x
44		ATC message(3) decoded	Process ATC message(3); read-back	2	x
45		ATC message(3) decoded, and having read the message back for confirmation	Adjust radio frequency	5	x
46		Radio frequency adjusted	Contact tower	5	x
47	1278	PF requests gear down	Gear down	3	
48		Gear down activated	Check for green indicators of gear lock	2	
49	1299	G/S intercepted at 5.5 NM from runway	Call 'Glideslope captured'	2	x
50		Target velocity not maintained	Observe the decrease of airspeed below the set target	2	

Continued on next page

Continuation of Table 5.2

Task #	Time [s]	Trigger	Task	dt [s]	Ex. Tr.
51		Decrease in airspeed observed	Update SA{airspeed dropping below target set on MCP, possible cause}	2	
52		Updated SAairspeed dropping to below target	Warn PF of airspeed decreasing below target	2	
53	1301	ATC message(4) Updates crew over: - clearance for landing	Decode ATC message(4)	1	x
54		ATC message(4) decoded	Process ATC message(4); read-back	4	x
In the case of a continued landing; PF decides to continue the landing, as the aircraft reaches an altitude of 1,000 ft					
55	1307	PF communicates the decision to continue the landing to PNF	Warn PF of the need for a go-around for an unstabilized approach	3	
56	1310	PF requests Flaps 40	Set Flaps 40, check conditions and confirm	4	
57	1350	PF requests to warn the cabin crew	‘cabin crew take your seats’	2	
58	1354	A/T not disconnected, and, amber band shown around airspeed indicator	Detect the presence of an amber band around the indicated airspeed	2	
59		Amber band around airspeed detected	Realize the low airspeed	2	
60		Low airspeed realized and, communicated with PF about the near-stall airspeed	Initiate the approach to stall recovery	2	
Concluded					

As it would have been expected, PNF’s tasks will complement the performance of the PF, serving as a backup and an additional source of warnings to alert the PF in the event of a critical conflict, or in the event of an insufficient performance by the PF.

5.2. TASKLOAD ANALYSIS OF REFERENCE EVENT SEQUENCE

Having defined the crew’s responsibilities throughout the operation in terms of the two task-lists in Section 5.1, one can next proceed by assessing the crew’s behavior and expected taskload under the reference event sequence of Flight TK1951. The objective of the assessment will be to establish the taskload the crew will be subjected to throughout the operation, to study its magnitude and the effects on the crew’s ability in executing their responsibilities. Considering the distribution of flight responsibilities in between the two crew members, this section will only model PF's ability to execute his or her tasks. This is achieved by a coupling of PF's accumulated taskload vector at any point throughout the operation, with an application of the two human's control modes of Chapter 4 to PF's mind status.

The PF's flight responsibilities, presented as tasks in Table 5.1, each are subjected to own times of origin and duration. As such, an actual timeline can be set up, according to which the PF will execute the tasks. As it can be extracted from Table 5.1, various tasks are introduced to PF at the same time, indicating the need for the pilot to execute the tasks simultaneously. However, since a simultaneous execution of tasks will not be practical for the PF, queues of tasks will be formed, whose correct completion will depend on PF's ability to fully acknowledge and execute the tasks in the correct sequence. As such, the pilot's taskload can be defined as the vector containing the queued tasks waiting for completion. This will assist in highlighting the instances, at which the PF will be subjected to a taskload of more than a single task to be executed. The assessment aims at identifying such bottlenecks in PF's performance and the relationship between these bottlenecks, PF's decision-making ability and ultimately, the safety of the operation.

5.2.1. ASSUMPTIONS

It should also be noted that any delay or failure of the operator in executing a component of the taskload vector will have a direct influence on the operator's ability in realization and completion of the remainder components of the taskload. A delay will result in pushing the execution time of any new incoming task to a later time slot, or ultimately preventing the pilot from detecting and adding the task to his or her taskload vector, jeopardizing the SA of the pilot with regards to the overall task list to be conducted. For that, assumptions must be made constructing the boundaries of the simulation.

The first assumption relates to the definition of a threshold presenting the barrier that separates the two possible control modes of the pilot. It is assumed that the pilot will shift from a tactical mode into an opportunistic mode, as the number of tasks in his or her current taskload vector exceeds three tasks.

The second assumption relates to the pilot's response to a stressful situation. Having exceeded the stress threshold, the pilot speeds up his or her reaction time, in order to be able to manage the expanded taskload. It is assumed that the pilot will be working at twice the regular pace, once modeled at an opportunistic mode.

The third and final assumption relates to the recovery procedure of a pilot from an opportunistic mode. It is assumed that the pilot will only fully recover from a stressful condition and change back to a tactical mode, only after the size of the taskload vector has reduced to one complete task below the stress threshold. As such, for a pilot having exceeded the stress threshold of three, he or she can only be modeled under tactical mode again once the taskload vector has been reduced back to two consecutive tasks.

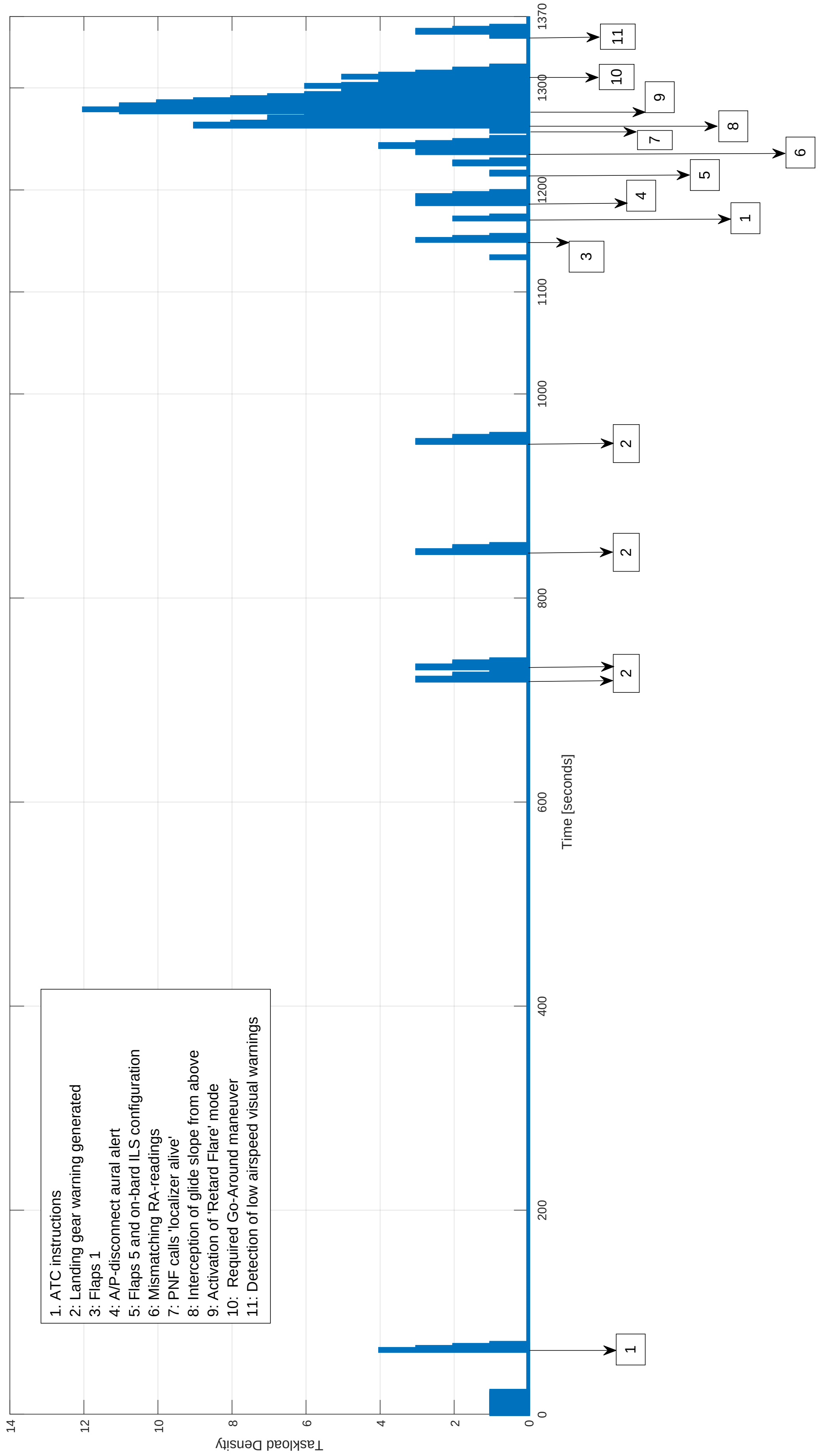

Figure 5.1: Development of PF's taskload density at the reference scenario

5.2.2. TASKLOAD FORMATION

Figure 5.1 illustrates the variation of PF's taskload density throughout the operation. Using the task list introduced in Table 5.1, the taskload density is constructed at each time step along the operation, t_i, starting at zero *seconds* and running to 1,370 *seconds*. The group of tasks associated to the illustrated jumps in taskload densities are mentioned in Figure 5.1.

As it can be seen, the taskload density throughout the reference scenario experiences numerous periods of extreme changes in its value. However, the taskload density is at its peak when the PF is tasked to detect the activation of the 'Retard Flare' mode of the A/T, after he or she has reconfigured the aircraft for the interception of the glide slope from above. In order to better understand the development of the taskload density, and the changes expected in PF's performance rate, the following looks deeper into the development of the taskload density at three instants along the operation. These correspond to the three jumps seen in Figure 5.1, at times 62, 719 and 1,262 *seconds*. The results are shown in Tables 5.3 to 5.5.

Per each table, the period prior and after the execution of the tasks are shown, in order to best show the shift in between the control modes. Two representations of taskload and control modes are provided per table. The left representation of taskload and control modes corresponds to how the pilot perceives the incoming taskload variation, and the influence it has on his or her change of control mode. With the stress threshold defined at three consecutive tasks, the corresponding control modes are next indicated. A red color indicates an opportunistic mode, while a green color indicates a tactical mode.

Next, given the assumptions described earlier in 5.2.1, the resulting control mode behavior of the pilot are shown in the right section of the table. The second grouped column of TL will thus include an 100% increase in reaction speed of the pilot. The use of a light green, at any instant in time, indicates that the pilot would have been acting at an opportunistic mode, had he or she not been acting at twice the normal reaction time.

It should be understood that Tables 5.3 to 5.5 do not represent the taskload variations for every time increments of one *seconds*. A more detailed representation of the entire duration of the operation is available in Appendix D.

Time Into Operation: 62 seconds

The first instant in time at which the taskload gets a significant jump and switches into an opportunistic mode is related to a time of 62 *seconds* into the operation, at which the ATCo informs the crew of their approach to Runway 18R. The simulations do not project a severe taskload, and as it can be seen in Table 5.3, the PF is able to restore his or her tactical mode within three *seconds* after the task execution is initiated, given a successful completion of the tasks. Given no system failure on-board, the PNF continues to back up the PF through monitoring the flight components and completing the task cluster PNF_{vii}, 'Air-Ground Communications'. As such, the PF is able to focus on his or her tasks related to the specific task type of 'Aviate'.

Table 5.3: Initiation of taskload densities at different control modes, at time 62 *seconds*

			TL and corresponding CM, at			TL and CM at 2x Speed, at		
Time [s]	**Originating Task #**	**T.L.**	**TH: 3**	**TH: 4**	**TH: 5**	**TH: 3**	**TH: 4**	**TH: 5**
59	-	0				0	0	0
60	-	0				0	0	0
61	-	0				0	0	0
62	3-6	4				4	4	4
63	-	3				3	3	3
64	-	3				2	2	3
65	-	2				1	1	2
66	-	2				0	0	2
67	-	1				0	0	1
68	-	1				0	0	1
69	-	0				0	0	0
70	-	0				0	0	0
71	-	0				0	0	0
								concluded

Time Into Operation: 719 seconds

A more interesting event occurs at the time of 719 *seconds*, at which the landing gear warning is sounded for the first time in the operation. As it was also illustrated in Figure 5.3, three tasks are modeled for the PF at a time of 719 *seconds*, through which the PF will have to observe, understand and communicate the findings to PNF.

Illustrated in Table 5.4, considering the threshold of three continuous tasks, the PF immediately enters an opportunistic mode. Operating under a stressed and opportunistic mode, as it was outlined in Table 4.36 in Section 4.2.11, the PF may fail to detect the warning at all, or to simply ignore the warning and fail to understand why the warning was generated.

The occurrence was experienced on Flight TK1951, in a very identical manner. The PF observes the aural warning, however, although the simulations result in a taskload size equal to the stress threshold, the PF still fails to analyze the warning and to communicate the results with PNF. As such, the crew's SA of the malfunctioning LRRA can not be updated. The jump in taskload explained here is repeated for a total of four times throughout the operation, where the PF fails to execute his or her task cluster PF_i in all events. This is while the taskload is only at three continuous tasks for all of the four events mentioned here, indicating a just-opportunistic control mode.

The crew is assumed to be highly trained, and the control mode at the time of execution cannot fully justify the significant lack of performance, especially since no other demanding tasks are modeled at this time. As such, one will have to search elsewhere for the reasoning behind the PF's failure in fully executing his or her tasks in

Table 5.4: Initiation of taskload densities at different control modes, at time 719 *seconds*

		TL and corresponding CM, at				TL and CM at 2x Speed, at		
Time [s]	**Originating Task #**	**T.L.**	**TH: 3**	**TH: 4**	**TH: 5**	**TH: 3**	**TH: 4**	**TH: 5**
716	-	0				0	0	0
717	-	0				0	0	0
718	-	0				0	0	0
719	7-9	3				3	3	3
720	-	3				2	3	3
721	-	2				2	2	2
722	-	2				1	2	2
723	-	2				0	2	2
724	-	2				0	2	2
725	-	1				0	1	1
726	-	1				0	1	1
727	-	0				0	0	0
728	-	0				0	0	0
729	-	0				0	0	0
								concluded

observing, understanding and communicating the warning with PNF, as witnessed on Flight TK1951. The purpose of this simulation is not to put the blame on any party involved in the operation, and as such, it suffices to outline potential contributors to the failure of the PF in analyzing the generated warning.

The nature of Flight TK1951 can be considered as a potential contributor. As a Line Flying Under Supervision (LIFUS), the Captain (CA) was responsible for instructing the First Officer (FO) throughout the flight. As such, the captain would have been subjected to a constant taskload throughout the flight, possibly influencing his ability to fully comprehend the flight status at all times.

Time Into Operation: 1,262 seconds

The taskload peak occurs at a time of 1,262 *seconds* into the operation, corresponding to the initiation time of task number 40. Next, the period of time corresponding to the most severe taskload size is studied in more details, with a representation of the variation of the taskload given in Table 5.5.

Table 5.5: Initiation of taskload densities at different control modes, at time 1,262 *seconds*

Time [s]	Originating Task #	TL and corresponding CM, at				TL and CM at 2x Speed, at		
		T.L.	TH: 3	TH: 4	TH: 5	TH: 3	TH: 4	TH: 5
1256	-	0				0	0	0
1257	39	1				1	1	1
1258	-	0				0	0	0
1259	-	0				0	0	0
1260	-	0				0	0	0
1261	-	0				0	0	0
1262	40-48	9				9	9	9
1263	-	9				8	8	8
1264	-	8				7	7	7
1265	-	8				6	6	6
1266	-	7				5	5	5
1267	-	7				4	4	4
1268	-	6				4	4	4
1269	-	5				3	3	3
1270	49-50	7				5	5	5
1271	-	6				4	4	4
1272	-	6				3	3	3
1273	-	6				3	3	3
1274	-	5				2	2	2
1275	-	5				2	2	2
1276	51-56	11				7	7	7
1277	57	11				7	7	7
1278	58	12				7	7	7
1279	-	11				6	6	6
1280	-	11				5	5	5
1281	-	11				5	5	5
1282	-	11				4	4	4
1283	-	10				3	3	3
1284	-	10				3	3	3
1285	-	10				2	2	2
1286	-	9				1	1	1
1287	-	9				0	0	0
1288	-	8				0	0	0
1289	-	8				0	0	0
1290	-	7				0	0	0
1291	-	7				0	0	0
1292	-	6				0	0	0

Continued on next page

Continuation of Table 5.5

Time [s]	Originating Task #	TL and corresponding CM, at				TL and CM at 2x Speed, at		
		T.L.	TH: 3	TH: 4	TH: 5	TH: 3	TH: 4	TH: 5
1293	-	6				0	0	0
1294	-	5				0	0	0
1295	-	5				0	0	0
1296	-	5				0	0	0
1297	-	4				0	0	0
1298	-	4				0	0	0
1299	59-60	5				2	2	2
1300	-	5				1	1	1
1301	61	6				1	1	1
1302	-	5				0	0	0
1303	-	4				0	0	0
1304	-	4				0	0	0
1305	-	3				0	0	0
1306	-	3				0	0	0
1307	62-63	4				2	2	2
1308	-	4				1	1	1
1309	-	3				0	0	1
1310	64-66	5				3	3	3
1311	-	4				2	2	2
1312	-	4				2	2	2
1313	-	3				1	1	1
1314	-	3				1	1	1
1315	-	2				0	0	0
1316	-	2				0	0	0
1317	-	2				0	0	0
1318	-	1				0	0	0
1319	-	1				0	0	0
1320	-	1				0	0	0
1321	-	0				0	0	0
1322	-	0				0	0	0
								Concluded

At the time of 1,262 *seconds*, nine tasks are added to PF's task list. The sudden jump in taskload results in PF's control mode to switch from a relaxed status to a heavily opportunistic mode. Although the PF will be acting at twice the regular reaction time, the PF fails to recover from an opportunistic mode before a time of 1,285 *seconds*. As such, the PF is opportunistically modeled for 23 *seconds*, during which the pilot will have to understand and make decisions on crucial aspects of flight. These include realization of the need to intercept the glide slope from above and the relevant reconfiguration of the aircraft, realization of the early activation of the 'Retard Flare' mode of the A/T, and the relevant reaction to disengage the A/T.

The tasks mentioned above were distributed and model earlier in Chapter 4 under PF's task clusters PF_i, 'Conflict Sensing', PF_{iii}, 'Sensor Failure Resolution', and PF_{vii}, 'Emergency Actions'. The description of PF's performance under an opportunistic mode for these clusters outlined the significant reduction in PF's performance. In addition, PF's behavior can be modeled as tactical after the 1,285 *seconds* mark, only because the pilot starts performing the tasks at 200% the normal reaction speed. This enforces a stressed behavior into the PF's performance, and following the descriptions in Chapter 4 of the pilot's reduced performance while stressed, the overall risk of making an error within this period of the operation increases significantly.

Using an enlarged stress threshold of four or five, for the purpose of delaying the transition to an opportunistic mode, also fails at providing a significant improvement in the PF's control mode. The taskload peak of the reference scenario is considered too great to be tactically handled by the PF, and as such, the pilot remains subjected to a jeopardized performance, regardless.

5.2.3. TASKLOAD DENSITY VS CONTROL MODE

In the event of a threshold (TH) of three, the majority of the tasks along the entire duration of the operation will have to be operated under an opportunistic mode. In fact, for almost 84% of tasks, the taskload density at the time of execution of the task is equal or larger than the stress threshold of three. The simulation models the PF's performance as opportunistic for a worrying 74% of the tasks, in which four or more tasks are constantly queued in his or her taskload. The taskload density increases to a significant value of 12 tasks at the time of 1,278 *seconds*, as it can be seen in Figure 5.1. A 200% increase in PF's reaction speed only reduces the taskload peak to a value of nine tasks.

With a total of 19 tasks introduced within only eight *seconds*, the pilot is locked in an opportunistic mode. This outlines the difficulty for the pilot to fully focus on his or her tasks and make a successful assessment of the conditions, prior to making and executing a resolution act.

Increasing the stress threshold to four continuous tasks allows the PF to execute 37% of the tasks at an opportunistic mode, while this value is further reduced to 27% for the case of a stress threshold of five. Although the ratio of tactical-to-opportunistic mode improves significantly when moving from a threshold of three to five, this has little practicality. Considering the description of a human's cognitive performance abilities and the relevant analysis given in Chapter 4, a PF is not capable of possessing sufficient decision-making abilities under such conditions.

5.3. QUANTITATIVE ASSESSMENT OF REFERENCE EVENT SEQUENCE

Section 5.2 outlined the extreme conditions related to the PF's heavily loaded taskload at crucial periods throughout the reference operation. The objective of this section will be to establish a quantitative likelihood estimate of success, given the results of Section 5.2. As such, the outcome of the assessment will be presented using a likelihood probability of completing the entire operation and associated tasklist under a normal and safe condition.

For this purpose, the results of Section 5.2 relating to PF's taskload and control mode throughout the operation will be used to assess the success likelihood of the reference operation.

In order to achieve more insights into the potential roles played by contributors other than PF's performance rate, in the formation of the overall success of the operation, different variations of the operation are considered next. For the purpose of constructing the variants of the reference operation, two of the main operational circumstances experienced in the reference operation scenario are used. The first relates to the failure of LRRA-1, while the second deviation implements an short runway line-up, as opposite to the late line-up of the reference operation. Per variant scenario, the PF's tasklist is reconfigured to match the new flight conditions, followed by an analysis of taskload formation and success likelihood, similar to that of the reference scenario.

5.3.1. ASSESSMENT METHODOLOGY

The objective is to assess the likelihood that the PF could have safely and completely executed his or her tasks, indicating a safe outcome for the operation. The definition of a safe operation is based on the distinctive human's performance levels presented in Chapter 4. An all-thorough tactically executed operation is considered to provide a conflict-free flight experience and a safe outcome. This assessment compares, per operation scenario, the ratio of the opportunistically-executed tasks to those which are performed by the PF under a tactical mode.

In order to compute the likelihood of success of the operation, the actual success probability of the operation is computed first, which is next divided by the success probability of the same scenario if completed fully tactical. Equation 5.1 provides the suggested method of computing the likelihood probability of how close the actual operation is to a safe operation:

$$L = \frac{\prod_{i=1}^{N}(1-\varepsilon^T)^{\chi^T}(1-\varepsilon^O)^{\chi^O}}{\prod_{i=1}^{N}(1-\varepsilon^T)^{\chi^T}} \tag{5.1}$$

where,

- L is the likelihood of the specific realization of the operation occurring under safe and tactical conditions,
- ε^T is the probability of error under a tactical mode,
- ε^O is the probability of error under an opportunistic mode,

- χ^T is equal to one, if the task is attempted by the pilot while operating at a tactical mode; zero otherwise,
- χ^O is equal to one, if the task is attempted by the pilot while operating at an opportunistic mode; zero otherwise,
- i indicates the current task at time t, and
- N is the total number of tasks.

The success likelihood of the scenario is thus calculated as follows. Per task, using the taskload vector analysis, the corresponding control mode is noted. Based on the control mode, the corresponding probability of error is used for that specific task. With a ten-step differences, a pilot functioning under a tactical mode is subjected to an error probability of 0.01, whereas an opportunistic pilot will be subjected to making errors at a probability of 0.1. This will help clearly distinguish between the performances under the two control modes.

Repeating the process for the entire taskload vector, and dividing the outcome by the total probability of completing the task list while acting under a tactical mode provides the final outcome for the success likelihood of the scenario. It should be understood that doing so, will indicate that unless the entire actual operation takes place at a tactical mode, the likelihood will always be smaller than one.

For the purpose of representing the likelihood results, the entire range of one to five is used for the stress threshold. The reasoning behind this decision is simply to help illustrate any sudden increases in likelihood. However, it should be understood that the analysis of a threshold below three continuous tasks is beyond the scope of this report.

5.3.2. ASSESSMENT RESULTS

Figure 5.2 illustrates the results of the analysis of success likelihood probability of the reference operation. Regardless of the stress threshold, the outcome of the likelihood function is significantly low for all simulations. An increase of the stress threshold to five continuous tasks only manages to improve the success likelihood of the operation to a value of only 9.23%. As such, it the likelihood results back up the hypothesis that the conditions throughout the reference scenario enforce a significantly difficult and demanding taskload to the PF, that cant not be tactically handled.

The extremely small indicators of likelihoods presented in Figure 5.2 can also be directly linked to PF's taskload density, presented in Figure 5.1. Although it was suggested in Section 5.2.2 that an enlarged threshold reduces the ratio of opportunistic to tactical significantly, it is the magnitude and duration of the taskload peak that causes the small likelihoods. Locked in an opportunistic mode, the PF is forced to perform a majority of crucial tasks at a stressed and hectic environment, regardless of the stress threshold chosen.

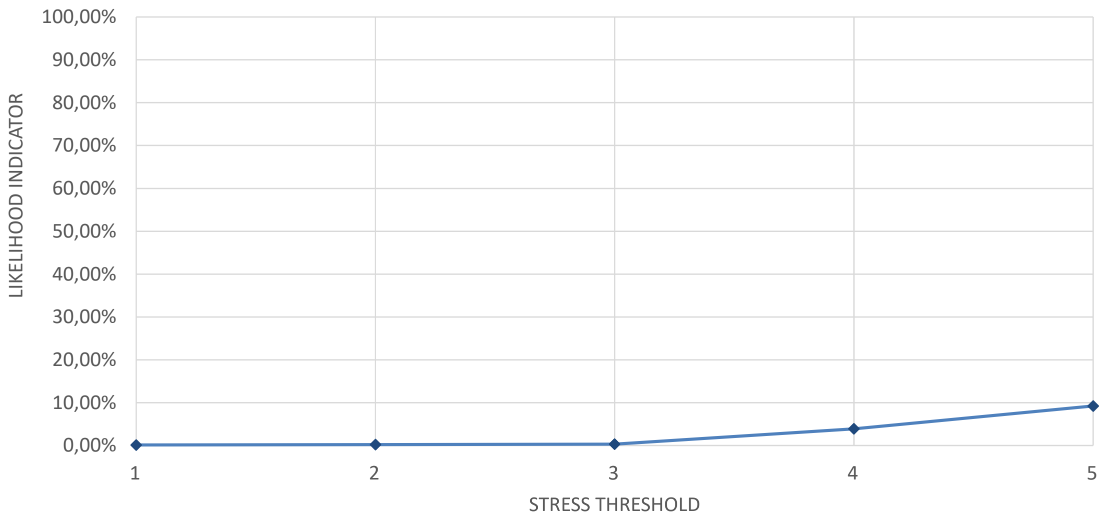

Figure 5.2: Success likelihood of reference scenario against stress threshold

Next, in order to study and prove the hypothesis made above regarding the abnormal and impractical conditions of the general scenario, different variations of the scenario are modeled.

5.4. Quantitative Assessment of Other Scenario Variants

The variants of the reference scenario focus on two aspects of the flight, namely the functioning status of LRRA-1 and the method of intercepting the localizer. Per scenario variant, the changes in the operation and the tasks omitted are outlined. The purpose of the removal and simplification of PF's task list is to only show the level of comfort this would bring to the PF and the consequences on PF's control mode and success likelihood of the operation. It is not meant to indicate a task-free PF.

5.4.1. Introduction of Scenario Variants

In total, three variations of the reference operation are considered. For the convenience of the reader, the reference event sequence modeled in Section 5.2 included a 'short line-up, and a faulty LRRA-1'.

Scenario One: Short Line-up and Functioning LRRA-1

The first scenario variant considers the scenario in which the LRRA-1 component is no loner providing erroneous RA-1 outputs. The localizer signal is still to be intercepted at a distance smaller than the 6.2 *NM* away from the runway threshold. As such, the task list will still include the tasks to do with the reconfiguration of the aircraft for the interception of the glide slope from above. This scenario will thus help investigate the effect of a malfunctioning LRRA-1, without coupling it with a short line-up.

An indication of the tasks omitted from PF's reference task list, shown earlier in Table 5.1, is given below:

- Tasks 7-18, 33-35, and 49-50:
  Eliminating the presence of a malfunctioning LRRA-1 will omit the triggers

associated with the generation of a landing gear warning. As such, it will no longer be required of the PF to notice the warning, and update his or her SA of the malfunctioning LRRA-1 and its potential consequences on the remainder of the avionics.

- Tasks 25-27:
  With no mismatching data between the outputs of ADIRU-1 and LRRA-1, the left A/P would have not been disconnected, thus eliminating the triggers requiring the PF to re-engage his or her A/P.

- 53-56, 59-60, 66, and 68-70:
  Since LRRA-1 no longer produces erroneous RA outputs, the scenario will no longer include an automatic activation of the 'Retard Flare' mode of the A/T, since the requirements for an automatic change of the mode of A/T are no longer met. This results in the elimination of the tasks associated with the configuration of the AFDS components, and also those related to detection and correction of airspeed loss.

SCENARIO TWO: EARLY LINE-UP AND FAULTY LRRA-1

The second operation variant covers the flight scenario, in which the aircraft is guided by the ATCo such that the localizer signal is intercepted at a distance larger than the 6.2 *NM* threshold from the runway. As a result, the glide slope will be intercepted from below. The malfunctioning of the LRRA-1 remains present for this flight scenario. The scenario will thus help investigating the influence of a short line-up on the outcome of the operation.

An indication of the tasks omitted from PF's reference task list, shown earlier in Table 5.1, is given below:

- Tasks 42-48:
  Positioned such that the glide slope can be intercepted from below, the PF will continue with task number 41, in which the F/D command bars are observed and as a result, PF's SA of 'intercepting the glide slope from below' is updated. Considered as a normal ILS procedure, no further communication is modeled in between the two pilots, and tasks associated with configuring the aircraft to intercept the glide slope from above are omitted.

- Tasks 51-56, 59-60, 66, and 68-70:
  Given the elimination of PF's task number 47, in which the mode of the FCC was adjusted, the requirements for an automatic activation of the 'Retard Flare' mode of the A/T are thus not met. As such, triggers 51-60 are eliminated, not requiring the PF to detect and act upon an unexpected mode change of the A/T.
  As a result, the A/T remains in control of the airspeed, and no airspeed loss is experienced. This leads to the elimination of triggers related to tasks 59-60, 66, and 68-70, all related to the rapid loss of airspeed.

SCENARIO THREE: EARLY LINE-UP AND FUNCTIONING LRRA-1

Having assessed the effects of the two flight aspects of 'short line-up' and 'functioning LRRA-1' separately, the third and final scenario variant combines the other two variants.

As such, the malfunctioning of the LRRA-1 will not be included, and the aircraft will be assumed to intercept the localizer clear of the 6.2 NM mark.

- Tasks 7-18, 33-35, 49-50 :
  A fully working LRRA-1 will eliminate the triggers related to detection and comprehension of the aural landing gear warnings (Scenario One).

- Tasks 25-27:
  A correct RA-1 output, matching that of the ADIRU-1, will eliminate the possibility of an automatic disconnection of the A/P-A (Scenario One).

- Tasks 42-48, 53-56, 59-60, 66, 68-70:
  Eliminating the erroneous RA-1 outputs, in addition to the interception of the glide slope signal from below, ensures that the requirements for an automatic activation of the 'Retard Flare' mode of the A/T are no longer met. The result and the omitted triggers were detailed under explanation of Scenario Two.

Graphical representations of the development of taskload densities for all three scenario variants and the differences with respect to the reference taskload density are available in Appendix D.

5.4.2. SCENARIO-DEPENDENT TASKLOAD DENSITY

As described in the previous section, Scenario One is an indicator of the potential influences of a faulty altimeter on PF's taskload density, while Scenario Two projects the effects of a short line-up on the severity of PF's taskload.

As it can be understood from Figure 5.1, the is little taskload density building up in the first 700 *seconds* of the operation. As such, for the assessment of the scenario-dependent taskload densities, Figures 5.3 and 5.4 illustrate the development of the taskload density for both Scenario One and Two, for the time range of 700 to 1,370 *seconds*.

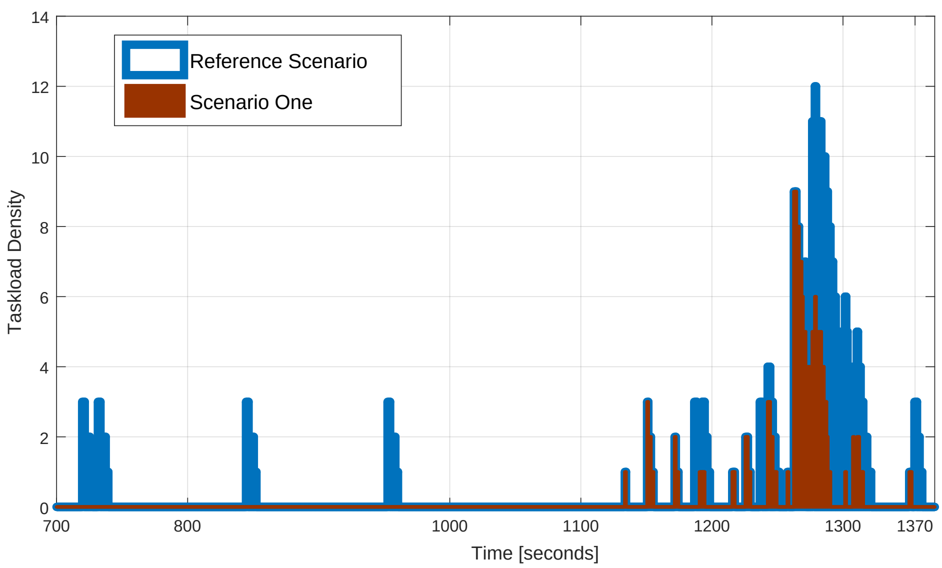

Figure 5.3: Taskload density; Reference scenario vs Scenario One

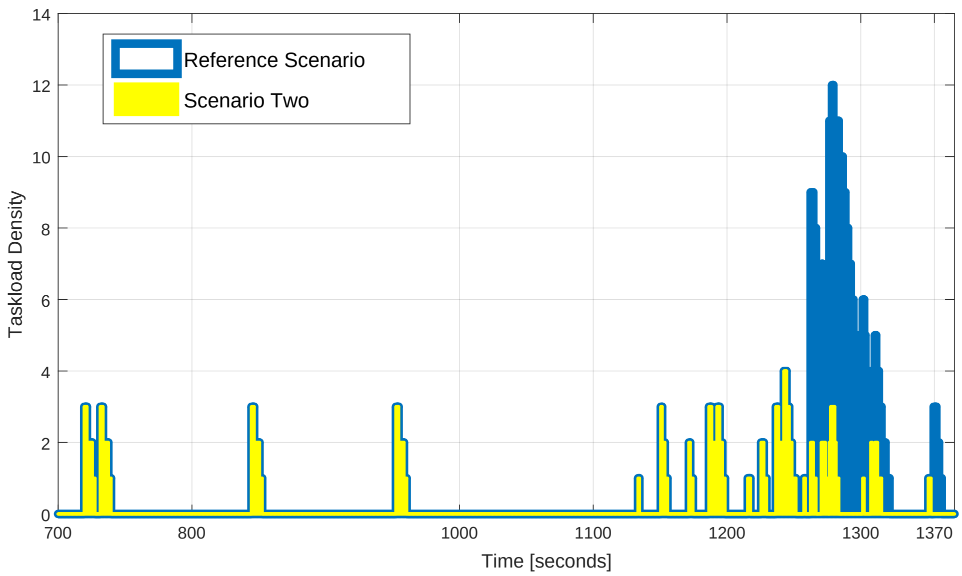

Figure 5.4: Taskload density; Reference scenario vs Scenario Two

In comparison to the developed taskload density under the reference scenario, Figure 5.3 shows a density development of similar pattern. The peak is 3 units smaller, occurring at a time of 1,262 *seconds*. This corresponds to the second largest peak of the reference scenario, at the time the localizer is intercepted and the pilot is still tasked with reconfiguration of the aircraft to intercept the glide slope from above.

Scenario Two, on the other hand, provides a significantly different development of the taskload density. Looking at Figure 5.4, one can see that the two peaks of the reference scenario and Scenario One are now removed, and that the pilot is subjected to an average peak of three consecutive tasks, distributed at numerous points throughout the operation. The omission of the short line-up from PF's task list has led to a scenario, in which the pilot is allowed to tactically assess his or her jet for almost the entire duration of the flight.

With the taskload density deviations of the two scenarios presented separately, Figure 5.5 allows the reader to have an overall look at the taskload variations in between the two scenarios throughout the entire duration of the operation. The severe taskload peak of Scenario One is clearly visible in Figure 5.5. The results of the contributions of a short line-up and a faulty altimeter equipment on the success likelihood of the operation will next be studied in the following section.

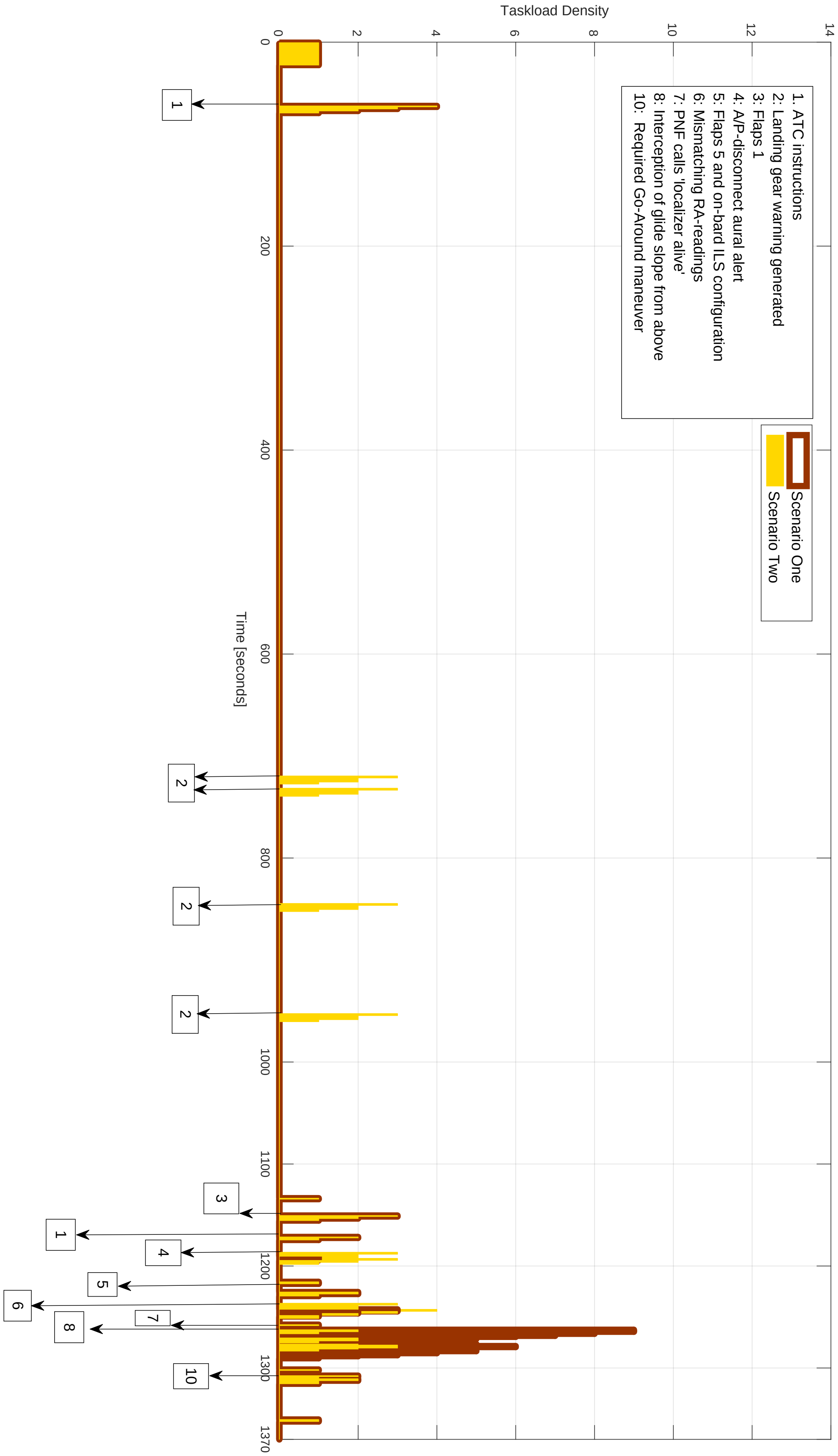

Figure 5.5: Taskload density; Scenario One vs Scenario Two

5.4.3. SCENARIO-DEPENDENT SUCCESS LIKELIHOOD

The success likelihoods of all scenarios analyzed, including the reference event sequence, are plotted in Figure 5.6. With the likelihoods of the reference operation detailed earlier in Section 5.3, a comparison of the likelihoods of other scenarios with the reference scenario is given next.

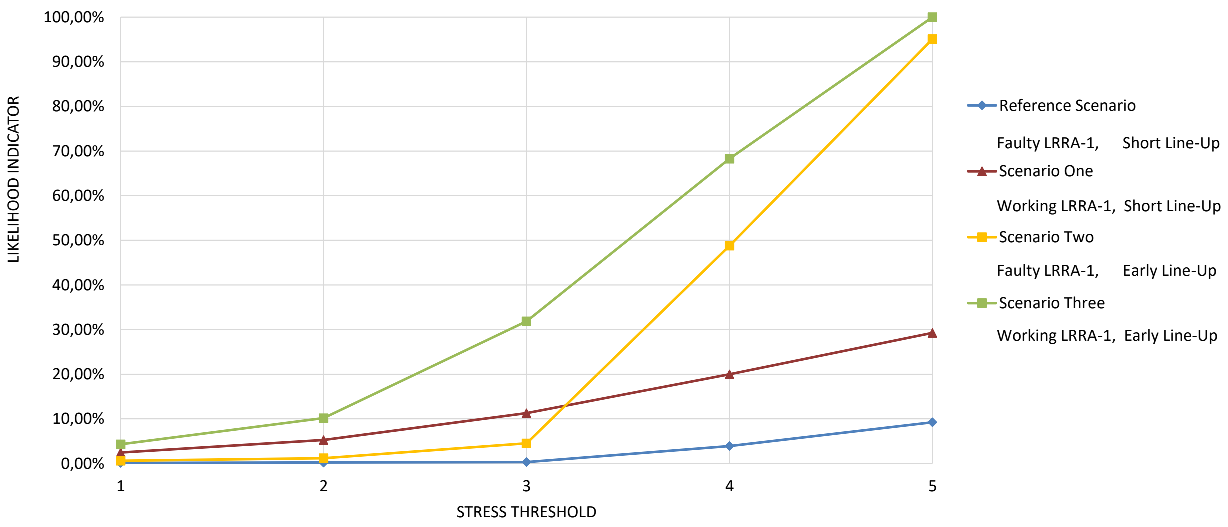

Figure 5.6: Success likelihood of all scenarios against stress threshold

The likelihood of Scenario One at a stress threshold of three has been improved to 11.28%, compared to the significantly small likelihood probability of 0.33% for the more demanding reference scenario. It can be suggested that in the event that LRRA-1 would have been functioning, the PF could have achieved around 11% improvement in his or her performance. This is a direct influence of the decrease in PF's taskload size, allowing him or her a slightly wider time horizon to make decisions. However, an increase of the threshold to five only assures an increased likelihood of just below 30%. This is considered insufficient, since it would indicate that PF will be performing a remainder of 70% of the tasks opportunistically, continuously vulnerable to a lack of performance.

When examining the stress threshold of three, Scenario Two actually fails in providing an improved success likelihood, generating a negative growth of 6.78% in likelihood compared to Scenario One. However, increasing the threshold to four already shows a massive improvement in the likelihood, where the likelihood probability increases from 19.98% of Scenario One to 48.8% in Scenario Two. The reasoning becomes clear when one studies the formation of the taskload vectors of the two scenarios. Scenario One results in the removal of multiple periods of constant taskloads of three, but fails to lower the PF's peak workload of nine tasks at the crucial time of intercepting the localizer.

On the other hand, although Scenario Two maintains the time slots with a constant taskload of three, the operation no longer includes the extreme peak of nine continuous tasks. The study of the second scenario thus helps better understand the severe and demanding conditions enforced on the PF, that follows the addition of a 'short line-up' to the operation.

It can only be expected that a combination of the two previous scenarios would further improve the PF's performance and the outcome of the operation. Observing the likelihood indications presented in Figure 5.6 for Scenario Three supports this hypothesis, where a threshold of three already projects a likelihood just short of 32%. With two unit increments, at a stress threshold of five continuous tasks, the likelihood of the operation at a fully tactical mode increases to exactly 100%. Although a stress threshold of five cannot be considered practical, it only serves to prove the potential contribution of the two flight aspects studied here to the formation of a demanding and severe taskload to be handled by the flight crew.

5.5. ANALYSIS OF SIMULATIONS OUTCOME

The three scenarios studied here provide further insights into the contributions of on-board technical failures and ATC procedures to the overall formation of the crash of Flight TK1951. The hypothesis regarding the formation of impractical conditions and the presence of severe conditions for the crew to operate sufficiently can now be backed up. Some final remarks are made here regarding the findings of the simulations.

A non-ideal condition of a malfunctioning LRRA-1 can indeed be considered as having provided the requirements for the unfolding of the crash as it happened on Flight TK1951. However, the results obtained from simulations of the scenario variants suggest the need for a much more crucial understanding and learning of this accident. Before covering these, a short discussion of pilot-related mistakes throughout the flight is provided below.

PILOT ERROR

The commonly occurring phenomenon of 'Pilot Error' can definitely be applied to numerous events of Flight TK1951. There is no doubt that despite the instants of extreme workloads throughout the flight, the crew's performance throughout some periods of lighter workload cannot be considered as sufficient and according to safety expectations. This was briefly described while examining PF's performance in between times of 716 and 729 *seconds*, detailed in Table 5.4.

The PF simply chooses to ignore the warnings for a total of four times, without including the PNF in a discussion and analysis of relevant causes and potential consequences on the remainder of the cockpit instruments. This is while the PF is barely at an opportunistic mode at these times. In fact, the presence of an aural warning also did not succeed in causing PF's entire attention, and with no actions taken by the PNF, all triggers go unnoticed and conflict remains unknown. The PF also fails to do so at time 1,270 *seconds*, for which no external trigger was available. The PF's failure at time 1,270 *seconds* can be explained by PF's opportunistic mode at this time, coming from an extreme taskload of nine continuous tasks. However, the same reasoning can not be mentioned for PF's failure at the other four events mentioned earlier.

The same applies for the PNF's performance, where the pilot fails to fully comprehend the situation and communicate the finding with the PF to raise awareness of any possible conflicts. The PNF is also subjected to a taskload of three continuous tasks upon activation of the landing gear warning, and still fails to act accordingly.

Furthermore, the two crew members are also found to be incapable of executing a continuous and sufficient monitoring of their systems, regardless of the control mode they are operating at. This prevents them from maintaining an updated SA of the overall flight conditions at all times. Figure 5.1 projects a hectic operation prior to and after the line-up of the aircraft with the runway. The opportunistically modeled PF fails to recover from the hectic environment, and as such doe snot update own SA of the data and visual warnings illustrated on the PFD regarding the airspeed. With no feedback and contributions from the PNF, PF remains uninformed and unaware of the development of a bigger conflict.

INFLUENCE OF ATC PROCEDURES

The analyses of Scenarios Two and Three show the significant role played by the application of a short line-up in the formation of a highly hectic taskload for both the PF and the PNF. As it was established in Figure 5.6, allowing the aircraft to line up with the runway prior to the 6.2 NM mark would have greatly improved the crew's performance, given the significant reduction in PF's taskload.

With no feedback from the uninformed cockpit crew regarding the malfunctioning LRRA-1, the ATCo could not have anticipated the possible consequences of a short line-up on the formation of the flight. However, the ATC procedures employed at the time of Flight TK1951 can be considered as risky, and inconsiderate of any subsequent difficulties imposed on the traffic.

The implementation of a short line-up was interpreted by the Air Traffic Control of The Netherlands (LVNL) to not cause any higher risk for the incoming traffic (Dutch Safety Board, 2010). The usage of a short line-up as a normal ATC procedure has been accepted mainly since no specific indicators and feedback have been received proving it otherwise. The benefits of a short line-up to enhance the noise abatement techniques can be another factor of convincing the ATC for incorporating it in their daily schedules. In fact, at the time of Flight TK1951's crash, LVNL confirmed that more than 50% of all approaches to Runway 18R are allocated with a turn-in maneuver between 5 and 8 NM from the runway threshold (Dutch Safety Board, 2010), indicating short line-ups with the runway.

"The most dangerous phrase in the language is...
'we have always done it this way.' "

Grace Hopper [1]

Although the argumentation on the practicality of a short line-up can be proved to be correct by the high number of safe daily landings, Flight TK1951's formation of event sequence proves exactly why it can be wrong to simply consider a procedure as 'correct', only based on the absence of any examples to prove it otherwise. The unfortunate combination of a malfunctioning LRRA-1 and a short line-up, led to the formation of extreme magnitudes of taskload to be handled by the crew of Flight TK1951, at a significantly short amount of time. As a result, an opportunistic and under-performing crew struggled to keep up with the occurrences aboard their aircraft, and failed to update their SA's accordingly. With an updated SA of the current flight status, the crew could have had the opportunity to monitor their equipment with a more clear objective, and as such, be able to detect the unexpected system changes and prevent the initiation of a stall.

It is found to be of extremely high importance for the ATC, in general, to avoid implementing any procedures which puts the performance of the incoming, or even an outgoing traffic for that matter, on the boundary of what can be considered as acceptable. The ATC should always allow for margins of safety given the continuous probability of failures in such a complicated socio-technical system. The implementation of safety margins has always been and will remain a topic of discussion, specifically when considering the cost efficiency of the operation. However, what can be taken away from the results is that the trade-off between safety, convenience and cost should never be dictated by the cost efficiency of an operation.

[1] American computer scientist and United States Navy rear admiral (1906 – 1992) (Gilbert and Moore, 2012)

6

CONCLUSIONS

The main objective of this report was to answer the question of why a non-ideal condition led to a catastrophic accident in the event of Flight TK1951, while the aircraft had previously landed safely under the same non-nominal condition. This question has been analyzed through agent-based modeling and simulation of the flight, the operation and the performance of the operators. In doing so, it was explicitly assumed that the flight was under the control of a normal two-pilot flight crew.

The agent-based modeling and simulation approach allowed for a reconstruction of the extreme conditions and the demanding taskloads to which the crew were subjected, during the most crucial moments of the flight. The reduced performance of the crew was broken down in terms of diminished abilities in observing, comprehending and projecting the current data available into potential conflicts in the future. The simulation allowed linking increased taskload density to reduction in crew's ability to reach out for an updated Situation Awareness, and as such, jeopardizing crew's decision making and reaction abilities.

The most undesired and unsafe flight operation was developed when simulating the event sequence in accordance to the actual occurrences of Flight TK1951. With the heaviest taskload peak in comparison to the other three scenarios analyzed, the reference scenario scored the lowest success likelihood, indicating highest rates of pilot's opportunistic behavior and failure rates. The lowest success likelihood thus corresponds to an operation with combined faulty altimeter and short runway line-up.

The malfunctioning of the radio altimeter and crew's failure in observation of the subsequent reduction of airspeed have been identified in the accident investigation report, as the trigger points for the development of the specific event sequence of Flight TK1951. The simulations however, provided an additional insight into the contributions of other flight-related occurrences to the success likelihood.

The simulation conducted allowed a comparison of the influences of both a faulty radio altimeter and a late line-up procedure on the safety of the operation. Upon simulating the variant scenarios, the significance of the contribution of the short line-up procedure to the overall success likelihood of the operation and taskload density of the flight crew were established. In fact, it was concluded from the simulation results that regardless of the functioning status of the radio altimeter, a short line-up leads to the development of severe conditions that could not have possibly been tackled safely by an opportunistically acting crew. In fact, an average performance improvement of 30.0% was established in the event the aircraft was allowed to execute an early runway line-up. The outcome of the simulations provide the reader with novel insights to what happened and how it happened that the same non-ideal flight conditions, that were safely flown previously, resulted in an catastrophic outcome.

As follow-up research, it is recommended for the agent-based simulation, to include the potential influences of identified pilot decisions that deviate from the actual flight, on the simulated flight path. This shall assist in providing an evolution model of the aircraft, making it possible to examine the trajectory flown as a result of variations in crew's performance rates.

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A

Detailed Description of Flight TK1951

This appendix aims at providing some background information and facts regarding the operation, including before, during and aftermath description.

First, a brief description of the nature of Flight TK1951 is given in Section A.1, followed by a description of the aircraft operated for this flight and the flight crew composition in Section A.2. Next, Section A.3 provides a brief description of the development of the crash landing of Flight TK1951. Section A.4 provides the reader with the findings of the official investigation team in regards to the cause of the crash landing of Flight TK1951. Once the abnormal and insufficient flight conditions are described in accordance to the investigation team, a brief history of the final moments of Flight TK1951 and the corresponding flight conditions are given in Section A.5. Last, Section A.6 contains the information regarding the history of the faulty altimeter installed on Flight TK1951 during the accident flight.

A.1. Introduction to Flight TK1951

The Flight TK1951 was a scheduled passenger flight by Turkish Airlines, taking off from Istanbul Ataturk Airport in Turkey at 08.23 hours local time (Dutch Safety Board, 2010). The flight was bound for its destination at Amsterdam Schiphol Airport in the Netherlands. There were a total of 128 passengers aboard the aircraft, in addition to a total of 7 crew members.

In the cockpit, while the first officer was the pilot flying, the right autopilot and flight directors were selected and active during the operation, with the left flight director active for the captain to fulfill his assisting responsibilities. As it was registered by the flight data recorder, the left altimeter had been providing the pilot side of the cockpit with an erroneous reading in regards to the altitude of the aircraft (Dutch Safety Board, 2010). This began shortly after taking off at Ataturk, as Flight TK1951 climbed through approximately 400 ft (van Ruitenbeek, 2012).

A.2. AIRCRAFT TYPE AND CREW COMPOSITION

Flight TK1951, with registration TC-JGE, was operated with a Boeing 737-800 aircraft, a two-engine narrow body aircraft with short to medium range. The aircraft, as seen in Figure A.1, was delivered to Turkish Airlines in March 2002, and was at the time of the accident 7 years old (Dutch Safety Board, 2010). TC-JGE had four cabin doors and was equipped with two emergency exits above each wing.

By March 2009, a month after the accident of Flight TK1951, a total of 1,469 Boeing 737-800s were in service worldwide (Dutch Safety Board, 2010).

Figure A.1: Boeing 737-800 TC-JGE, at Stuttgart Airport in 2006 (Juergen Lehle Photography, 2006)

Inside the cockpit, three cabin crew members were present for the entire duration of the flight. Following the nature of the flight as a Line Flight Under Supervision, the First Officer of this flight was being instructed by the more experienced Captain. As such, a safety pilot was placed inside the cockpit, for the purpose of providing assistance to the captain, through monitoring of the cockpit equipment and displays.

The captain, situated in the left seat, was the head pilot of Flight TK1951. Alongside him, the First Officer was situated on the right seat. During the final approach of Flight TK1951, the First Officer was the PF, while the Captain was acting as both the instructor and the PNF.

A.3. EVENTS LEADING TO THE CRASH

In the final moments of the approach for the Polderbaan runway at Schiphol airport, a sequence of events led up to a crash landing of the aircraft in a field at a distance of about 1.5 kilometers away from the runway threshold. From the 135 people aboard the aircraft, five passengers and four crew members died at impact. All three pilots were among the deceased.

While in descend for approach to Schiphol Airport, at about 8,500 ft the aural landing gear warning was heard, indicating the need for the landing gears to be retracted. As the aircraft continued its descend, it was directed by the Air Traffic Control for an ILS approach and landing on runway 18R. While the standard procedure for runway

18R includes an interception of the glide slope from below (Stackexchange, 2015) (Skybrary, 2014) (Collins, 2015), Flight TK1951 was vectored such that the glide slope was approached from above. However, the crew was aware of the specific procedure and was expecting a reduction of height and speed to intersect the slope from above (Dutch Safety Board, 2010).

A crucial malfunctioning in the cockpit, of which the captain seemed to have been aware (Dutch Safety Board, 2010), was a faulty altimeter on the side of the captain. While the first officer's primary flight display indicated the correct height, the captain's flight display indicated a wrong reading of -8 ft during much of the flight. From the Captain's words, it is suggested that he was aware of its malfunctioning, and went on to disregard the audio warnings regarding the landing gear for a total of 4 times during the approach. However, he failed to realize the effect it would have had on various other aircraft systems, such as the autothrottle. In fact, all three pilots in the cockpit failed to understand the significance of the problem, as the manuals for use during the flight did not contain any procedures for how to proceed in events of erroneous radio altimeter systems (van Ruitenbeek, 2012).

As a result of the incorrect altitude reading, at a height just above 1,000 ft the autothrottle prepared for touch-down, and thus moved the throttles back to an idle position, putting the aircraft into a retard flare mode. At this point, the thrust from both engines was reduced to a minimum value, hardly providing any thrust, while the autopilot kept the aircraft flying on the glide slope.

While it is generally required for an ILS approach to have the aircraft configured well 1,000 ft (Dutch Safety Board, 2010), the crew on Flight TK1951 was still occupied with their checklist as the aircraft was rapidly losing altitude and speed. As a result, the crew did not notice the reduction of speed to below the speed required for a continuous flight. In fact, the crew missed various indications and warnings, until the significant reduction in speed and the high pitch attitude of the aircraft led to a stall warning at an altitude of 460 ft (Dutch Safety Board, 2010).

While the crew was fighting to save the aircraft from stalling, they were still unaware of the relationship between the faulty altimeter reading and the reduction of airspeed (Dutch Safety Board, 2010). As such, their response in increasing the thrust was for the second time overcome by the incorrectly fed autothrottle. The throttle levers were again pushed back to the idle position, preventing the aircraft from gaining speed and recovering from stall.

Eventually, nine seconds after the first stall warning, after the captain had taken over the control, the autothrottle was disconnected and throttle levers were pushed fully forward as a last attempt in recovering the aircraft. However, since there was insufficient height above the ground to fully recover from a stall situation, the crew did not have enough time and the aircraft crash landed on a field at about 1.5 kilometers from runway 18R, as it can be seen in Figure A.2.

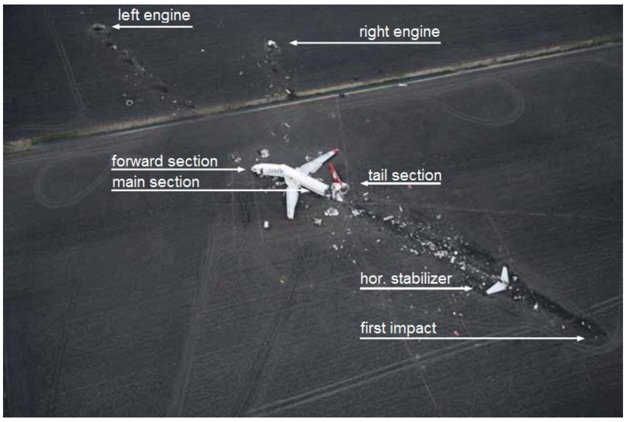

Figure A.2: Crash Site of Flight TK1951 (Dutch Safety Board, 2010)

At the moment of ground impact, the aircraft had a speed of 92 knots, coming to a stop after sliding for about 150 meters on the farmland (Dutch Safety Board, 2010). The aircraft suffered significant damage and was broken into three main parts, the front fuselage including the cockpit, the main fuselage from seat rows seven to 28, and the after fuselage including the tail section. The horizontal stabilizer and the main two landing gears were separated from the aircraft. Both engines were separated from the wings and found at a distance of about 100 meters from the fuselage. An illustration of the significance of the damage to the aircraft can be found in Figure A.3.

(a) The Tail Section (Dutch Safety Board, 2010)

(b) Front and Main Sections of the Fuselage (Dutch Safety Board, 2010)

Figure A.3: Condition of Flight TK1951 After Crashing

In regards to the fatalities, in total 5 passengers were killed, all situated in the business section of the aircraft. Among the deceased crew, all three pilots were dead, in addition to a flight attendant seated in the rear section of the aircraft, separated at impact from the rest of the main fuselage.

A.4. OFFICIAL CRASH INVESTIGATION REPORT

Since the accident of Flight TK1951, various organizations, individuals and official investigation teams have analyzed and investigated the crash, describing the event from different perspectives. This is indeed a crucial asset in thoroughly understanding the accident as it happened. An analysis of these reports, with the proper tools, can help clear the doubts as to if human error was solely responsible for the development of this crash. It will also help in realizing the extent to which technological error, and interaction between systematic and human agents contributed to it. Among these reports, two studies are of great importance for the purpose of this report. The first is the official report from the Dutch Safety board, DSB, issued in May 2009. The second is a previous MSc Thesis paper on Retrospective agent-based mental simulation of the accident, at the TU-Delft, in 2013.

The former report is an official report about the findings of the Dutch investigation team in regards to the accident, and the events that led to the crash of Flight TK1951. On the other side, the latter focuses mainly on a retrospective mental simulation of the crash, looking to see how agents' behavior and actions built up a sequence of events leading to the crash, and how the scenario could have been different, thus preventing the crash. The findings of the official investigation team is presented in this section.

As the official investigation team, the report of DSB is considered as the official and most complete study in terms of engineering and psychological analysis of the accident. During this analysis, consultations were given to the DSB (van Ettinger, 2013) from various other organizations, both in terms of manufacturing and operational entities in relation to the specific aircraft of the accident of Flight TK1951. This makes the findings of the report of DSB useful for the understanding and analysis of the events leading to the accident, and also for the identification of agents who contributed to the accident.

The report thoroughly describes the events as they occurred on Flight TK1951. While an overall summary of these occurring was presented in Section A.3, the report highlights on various conditions and circumstances which are believed to have had slight to main contributions to the final outcome.

SYSTEM MONITORING

The board indeed concludes that the malfunctioning of the left radio altimeter system caused a large reduction in speed, after the improper reading of the equipment led to a reduction of the total thrust to a minimal value too soon during the approach to runway 18R (Dutch Safety Board, 2010). The board also concludes that a failure of continuous and effective monitoring of airspeed and pitch attitude of the aircraft resulted in reaching the stall speed (Dutch Safety Board, 2010)(van Ruitenbeek, 2012). In addition, the approach to stall recovery was not implemented properly (Wilcutt and Harkins, 2012), leading to production of insufficient lift, and eventually crash-landing of the aircraft.

NON-STABILIZED APPROACH

The DSB also touches upon in-between conditions and circumstances which are of significant concern to the development of this accident. Going back to the moment before the final approach to Schiphol Airport, the approach is concluded to have been non-stabilized (Dutch Safety Board, 2010). A general rule prescribes the execution of a go-around at an altitude of 1,000 ft if the landing checklist has not fully completed by the time of reaching this altitude (Airbus, 2006). However, even though the crew were still busy with their tasks to prepare the aircraft for the landing, and while low visibility was present at the time (Dutch Safety Board, 2010), no go-around was performed. In fact, up to the point of stick shaker, the crew were still busy with preparing for the landing, indicating a non-stabilized approach. While the captain could have disregarded the non-stabilized approach as a threat to safely complete the landing, it however is believed to have assisted in the convergence of circumstances present during the final approach of Flight TK1951 which made the crash possible.

LINE-UP FOR RUNWAY

The next point outlined in the report by the DSB is the instruction issued by the air traffic control and its consequences on the flight path and altitude of aircraft, in combination with the wrongly fed flight management system. As a standard approach at Schiphol Airport, Flight TK1951 was instructed such that the localizer signal would be intercepted at 5.5 NM from the runway threshold, with the glide slope to be intercepted from above (Dutch Safety Board, 2010), as a noise abatement technique. According to the Air Traffic Control in the Netherlands, on certain conditions aircraft are instructed as such in order to permit an approach between 8 and 5 NM from the runway threshold. This approach is not an unsafe approach and can be safely executed (Dutch Safety Board, 2010), given the pilot is fully aware of the situation and the required adjustments.

However, although on an ordinary approach this would not cause a threat to the safety of a flight, on Flight TK1951 a different scenario was played. Following the procedure to intercept the glide slope from above, the aircraft had to reduce speed and lose altitude. After the 'retard flare' mode of the autothrottle put the thrust levers at an 'idle' position, this remained hidden from the crew as they were already expecting a reduction in speed and altitude as a standard procedure to intercept the glide slope from above. This made the crew unaware of the rapid and extreme deceleration.

RADIO ALTIMETER SYSTEM ERROR

The board also looks into the history of the malfunctioning radio altimeter system aboard the Boeing 737. While for the crew aboard the aircraft, the improper functioning of this equipment seemed surprising and of unknown consequences, the problem is believed to have not been an isolated one. In fact, not only Turkish Airlines, but also other airlines had been reporting the issue to Boeing for a long time before the accident of Flight TK1951. While Turkish Airlines tried various potential solutions, Boeing finally considered the problem as a technical and not a safety issue (Tosterling, 2010), as only some of the yearly reports were related to the activation of the 'retard flare' mode of the autothrottle.

It was stated by Boeing that significant and adequate warnings and indications were available to the crew to notice and counteract the issue in time (Tosterling, 2010).

However, the DSB is in disagreements with this decision, as through multiple events, Boeing had been warned of specific consequences, arising in particular cases of 'retard flare' mode activation of the autothrottle. Following the decision made by Boeing to treat the issue as a technical issue, it is believed that there is little to warn pilots to intervene in time and lack of proper knowledge can keep aviation prone to similar surprises.

LINE FLYING UNDER SUPERVISION

The fact that all three crew members in the cockpit failed to notice the warnings and indications for the low speed at which they were flying was a result of combination of various events. In addition to reasons such as the late stabilization of the aircraft for landing and the cover up of the rapid deceleration by the need to intersect the glide slope, the board also questions the efficiency of the presence of the additional safety pilot in the cockpit.

Although the safety pilot was expected to assist the captain in fulfilling his primary responsibilities in monitoring and ensuring a safe flight, while instructing the first officer, DSB concludes that the system of a safety pilot on board Flight TK1951 did not work as planned. While the safety pilot did make some comments during the approach in regards to the error in the altimeter system, and about the low speed after the stick shaker, he failed to properly monitor the speed and altitude, and warn the pilot of the reduction of the airspeed.

APPROACH TO STALL TRAINING

The DSB believes there is inadequate training rules when it comes to approach to stall training. The captain is believed to have had no exercises at all in dealing with approach to stall situations for many years. The board asks for an approach to stall training to be included in airlines' training.

In addition, the board finds it necessary for the manuals available to the pilots to contain information about potential consequences of a non-functioning radio altimeter system, or any other system for that matter. This is intended to enable the crew to make proper assessment of the consequences of their malfunctioning systems and the risk imposed to their operation.

INVESTIGATION REPORT SUMMARY

As it can be understood from the points outlined above, the report recognizes the negative impact of the faulty altimeter equipment aboard the aircraft on some crucial systems such as the autopilot and autothrottle, and thus identifies it as a main contributor to the formation of the events on Flight TK1951. However, the report does not hold the faulty equipment as a sole cause factor for the final outcome of the flight. In fact, various decisions aboard and also on the ground, and lack of proper understanding and teaching of systems interactions are believed to have contributed to the formation of the events during the final approach of the Turkish Airlines Flight TK1951.

A.5. CREW'S INPUTS DURING ILS APPROACH

Flight TK1951 was being flown by the first officer, who was receiving his LIFUS under supervision of his supervisor, the Captain of Flight TK1951. The intention was an approach, through a coupled ILS CAT I approach on the right computer (van Ruitenbeek, 2012). With the first officer as the Pilot Flying, PF, the right A/P computer, A/P B, was selected and active during the approach to the Schiphol Airport (Dutch Safety Board, 2010) (van Ruitenbeek, 2012).

As it was previously described, erroneous readings were recorded by the flight data recorder from the left radio altimeter system. These began shortly after take-off, as Flight TK1951 climbed through approximately 400 ft (van Ruitenbeek, 2012). Since the approach phase of Flight TK1951 is of main concern for the current report, the faulty radio altimeter and the subsequent effects on the avionics systems in contact with this system will be the center of focus. For this purpose, a detailed history of the flight in its approach phase will be provided in this section.

In order to fully study the events during the final approach and descend of Flight TK1951, Figure A.4 will be used. As it can be seen in Figure A.4, Flight TK1951 was coming in from the left side of Runway 18R, going to intersect the localizer, followed by the intersection of the glide slope and landing at Schiphol Airport. Point 1 on Figure A.4 indicates the arrival of Flight TK1951 at an altitude of 2,000 ft, at a speed of 221 knots.

At point 2, 17 seconds after point 1, 'Flaps 1' is selected for the flaps position. At point 2, radio contact with the Schiphol Approach is initiated. A time span of 7 minutes and 35 seconds is indicated between points 2 and 3. During this period, the aural warning regarding the landing gear is heard four times.

The phase from point 3 to point 4, is the aligning of the aircraft for the final approach. At the beginning of this phase, the aircraft is given instruction to fly heading 210 deg and is given the permission to start the approach. The aural warning regarding the landing gear is once again heard at this phase. This phase is concluded with the selection of 'Flaps 15' position.

Next, the aircraft proceeds to the intersection of the localizer. This is the phase from point 4 to point 6 in Figure A.4. At 10:23:58 hours, indicated at point 5, 'gear down' is implemented. This results in the termination of the landing gear warnings. Having intersected the localizer at point 6, the aircraft is now aligned with the Runway, at a heading of 184 deg. As indicated under point 6 in Figure A.4, the 'V/S' pitch mode is selected, where the glide slope is approached from above from an altitude of 2,000

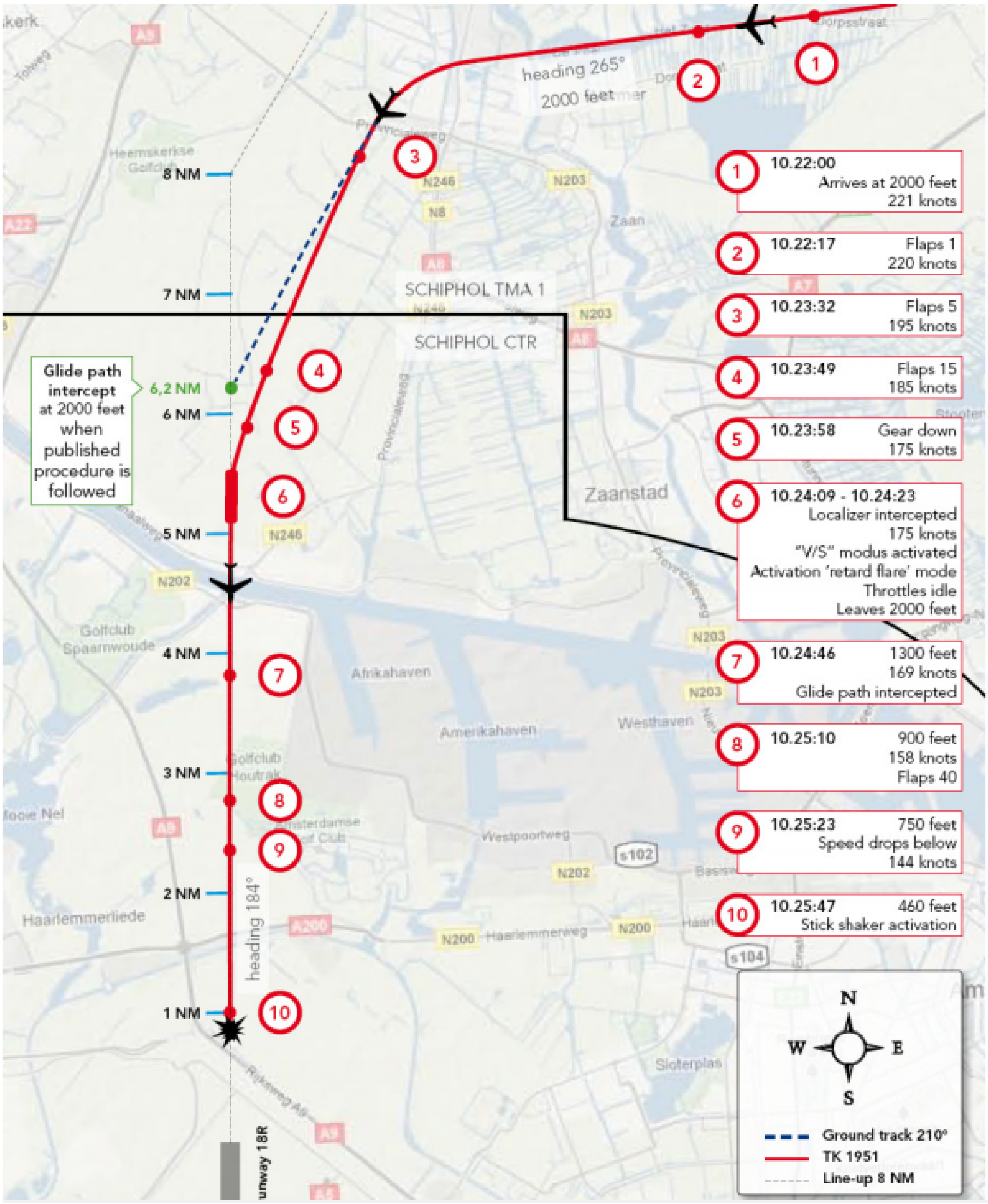

Figure A.4: Approach of Flight TK1951 (Dutch Safety Board, 2010)

ft. The A/T mode is automatically altered to 'RETARD', resulting in the automatic re-positioning of the thrust levers to an idle position.

The aircraft proceeds to start radio contact with Schiphol Tower after point 6. At 10:24:46 hours, point 7, the aircraft has intercepted the glide slope, and is traveling at a speed of 169 knots, with flaps in 'Flaps 40' position. While the aircraft is reaching 1,000 ft, the crew is still busy executing the checklist. At point 8, the aircraft has reduced its altitude further to 900 ft, traveling at a speed of 158 knots and flaps in 'Flaps 40' position. A landing speed of 144 knots is selected. The timing at which this was done will be discussed ahead.

The flight is continued at the phase from point 8 to 9, where the airspeed now drops below the selected landing speed of 144 knots. While having descended to 750 ft at point 9, the aircraft continues reducing altitude. At point 9, the aircraft is 2.5 NM away from the threshold of the runway, which reduces to 1 NM at point 10, when the aircraft is at an altitude of 460 ft.

At point 10, the activation of the stick shaker occurs, which is followed by the stalling of the aircraft and the crash landing of Flight TK1951 before reaching the runway 18R.

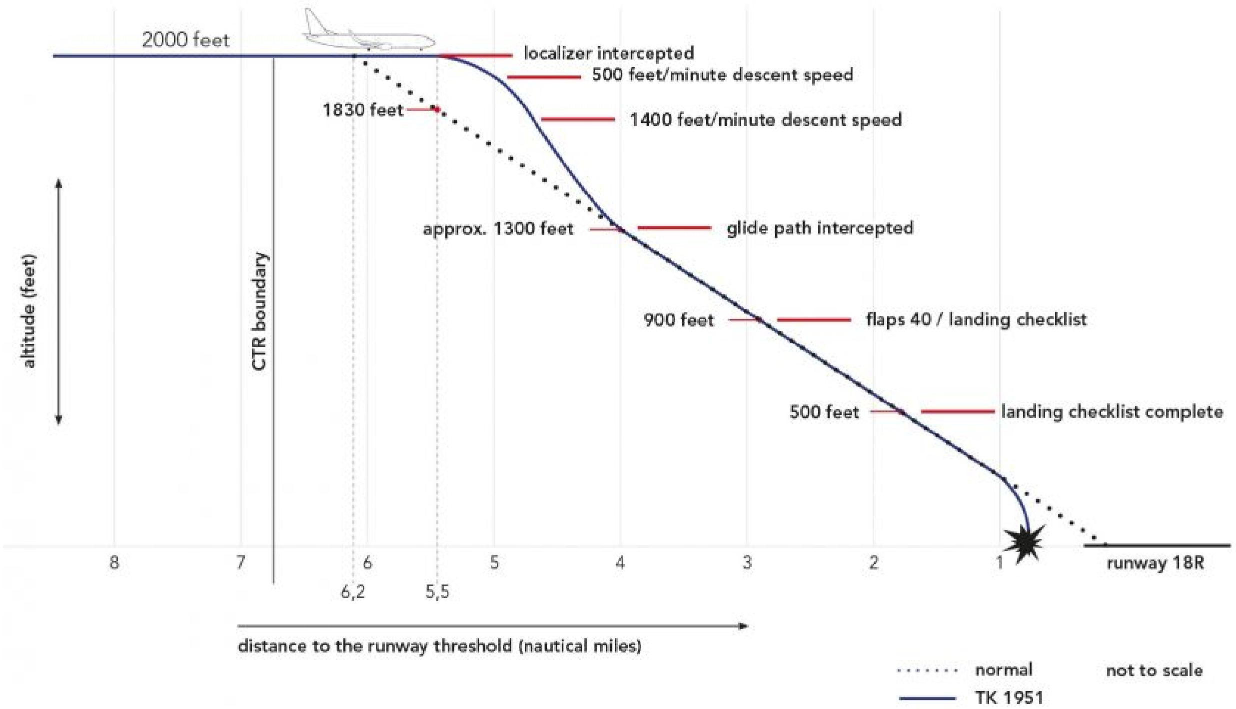

Figure A.5: Side view of approach of Flight TK1951 (Dutch Safety Board, 2010)

In addition, Figure A.5 provides a side view of the approach of Flight TK1951. The study of this figure can assist in understanding the events as they occurred in the last moments of Flight TK1951. The continuous line illustrated in Figure A.5 indicates the path of Flight TK1951, while a normal approach and landing is indicated by the dotted line. As it can be understood from the deviations in between the two lines, Flight TK1951 followed a different path prior to intercepting the glide slope signal. This is related to the different approach to intercepting the glide slope vector at Schiphol, namely the intercepting of the signal from above, as a noise mitigation measure. As such, the aircraft shows increasing vertical descend rates after having intercepted the localizer, and prior to the interception of the glide slope. A 1,400 ft/min descend rate is recorded as the aircraft is approximately 1800 ft above the ground. Similar to Figure A.4, the points at which the localizer and the glide slope were intercepted are illustrated in Figure A.5. These correspond to distances to runway threshold of 5.5 and 4 NM, respectively.

As it can be seen in Figure A.5, the landing checklist was only completed after the aircraft had already descended to 500 ft. Only then, as part of the routine tasks for the completion of the landing checklist, the cabin crew were warned by the cockpit crew to take their positions for landing. This can also be seen in Figure A.6, which indicates the timeline of actions performed by the cockpit crew between the interception of the localizer signal and the activation of the stall warning. Figure A.6 thus relates to the phases between points 6 and 10 in Figure A.4.

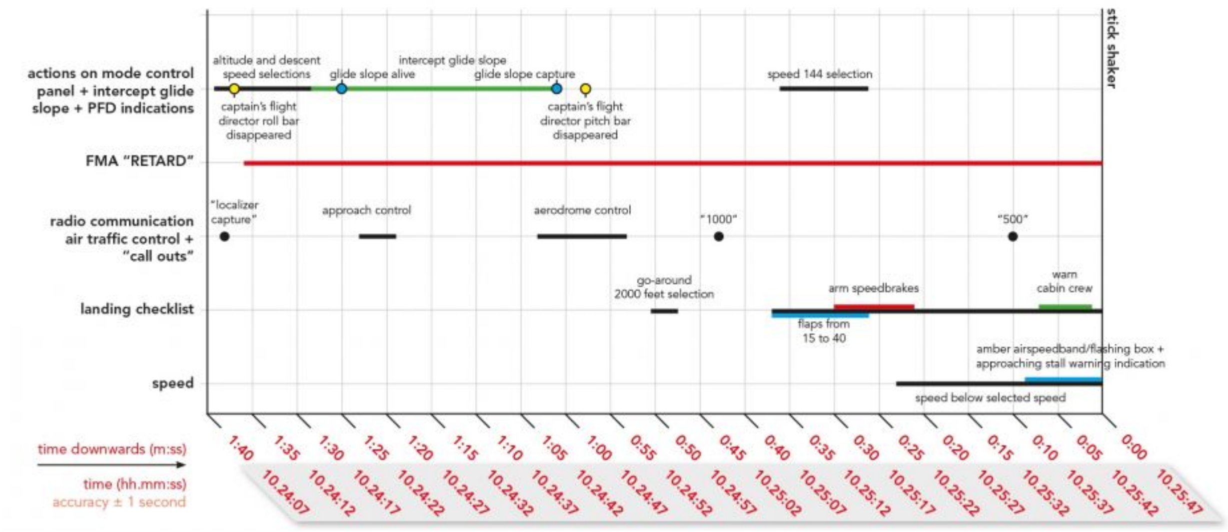

Figure A.6: Timeline of actions performed by the crew (Dutch Safety Board, 2010)

In regards to the selection of the 144 knots landing speed, while van Ruitenbeek's (van Ruitenbeek, 2012) briefing of the approach phase indicates a selection performed at the end of phase 6-7, the action timeline provided in Figure A.6 indicates otherwise. The illustration, provided by the Dutch Safety Board, DSB, indicates the selection of the 144 knots landing speed at 35 to 25 seconds prior to the activation of stick shaker. This would place it at the beginning of phase 8, in the time span in phase 8-9 on Figure A.4.

The accident of Flight TK1951 is concluded by numerous investigatory teams to have been the result of a string of events, and the convergence of these in the final outcome. As such, no single system or human fault, or event has not been held as primary and only wrongdoing and crash-causing element. In order to fully understand these events, and be able to examine the level to which they could have affected the outcome of the complete operation, one will need to obtain an in-depth understanding of system behavior and relationships between the numerous systems involved in an operation at this scale.

A.6. HISTORY OF FAULTY ALTIMETER SYSTEM

As it was stated earlier, the aircraft TC-JGE was seven years old at the time of accident of Flight TK1951. As an attempt to understand the cause behind the malfunctioning altimeter system, the maintenance documents of TC-JGE and the Turkish Airlines were examined by the Dutch Safety Board, the lead investigator for the crash of Flight TK1951.

It soon became apparent that problems with the radio altimeter system had been experienced in the entire first series of Boeing 737-800 aircraft owned by the Turkish

Airlines (Dutch Safety Board, 2010). These problems ranged from negative altimeter readings, like the case of Flight TK1951, to landing gear warnings and ground proximity system warnings. In fact, in 2012 Boeing received information with regards to other airlines facing the same problems with the radio altimeter systems on their aircraft. However, Turkish Airlines and other operators owning the Boeing 737-800 considered this issue as a technical problem and not a safety hazard (Dutch Safety Board, 2010).

The documentations of Turkish Airlines reveal that in total, in a period of one year from January 2008 to January 2009, about 3 years before the accident, 16 radio altimeter system faults were reported with regards to the TC-JGE aircraft. In total, 235 reports were made with regards to the 52 Boeing 737-800 aircraft aircraft of this airline (Dutch Safety Board, 2010).

While the real cause of the erroneous reading was never identified, various attempts were made to resolve the problem. Table A.1 presents the list of actions taken by the Turkish Airlines as a result of the irregularities in their radio altimeter systems:

Table A.1: Actions carried out by Turkish Airlines to resolve the faulty altimeter problem (Dutch Safety Board, 2010)

	Number of Actions Taken on	
Action Type	**TC-JGE**	**Complete B737-800 Fleet**
Antenna replaced	3	57
Antenna exchanged	2	24
Cleaned	1	8
System reset	5	49
Computer exchanged	2	44
Computer replaced	0	15
Tested	3	35
Other	0	3
Total	**16**	**235**

As it can be seen in Table A.1, the airline attempted several actions, such as installation of gaskets and moisture-proof wraps. While the replacement of the antennas resolved the problems, no permanent solution could yet be found. Apart from the physical corrections such as the gaskets and the wraps, the airline also approached the problem by changing computer equipment, which still did not fully fix the problem.

B

FLIGHT TK1951'S COCKPIT VOICE RECORDER DATA

Agent Abbreviations:

- PF : Pilot Flying
- PNF : Pilot Not Flying
- SP : Safety Pilot
- ATCo : ATC Operator
- WS : Warning System components

Additional Remarks:

- The English translation of the conversations, as provided by the investigatory body (Dutch Safety Board, 2010) has been used below.
- ATCo covers all conversations made by ground-based controllers.

Table B.1: Breakdown of tasks applicable to PF during the final approach

Agent	Time	Content	Remarks
PF	10:15:02	"Amsterdam Turkish 1-9-5-1 descending 70 speed 250"	
WS	10:15:06	Aural landing gear configuration warning horn - on	Crew do not address and discuss the warning

Continued on next page

Continuation of Table B.1

Agent	Time	Content	Remarks
ATCO	10:15:07	“Turkish 1-9-5-1 hello, proceed S-P-Y descend to 40, speed okay for ILS 1-8-R”	
AV	10:15:17	Aural landing gear configuration warning horn - off	Crew do not address and discuss the warning
WS	10:15:18	Aural landing gear configuration warning horn - on	
ATC	10:15:29	“Break, Turkish 1-9-5-1, direct S-P-Y, descend 4-0, I-L-S 1-8 Right”	
PF	10:15:35	“S-P-Y, 4-0, 1-8 Right"	
PNF	10:15:39	“40 set, instructor"	
PNF	10:16:01	“We will continue to VOR with the heading of 330 degrees and will continue till 12.1 miles, instructor"	
WS	10:16:33	Aural landing gear configuration warning horn - off	
PF	10:16:52	“Radio altimeter”	
WS	10:17:11	Aural landing gear configuration warning horn - on	
WS	10:17:13	Aural landing gear configuration warning horn - off	
PF	10:17:53	“Landing Gear”	
PNF	10:17:56	“OK, instructor"	
PNF	10:18:08	“All courses set on 184, I will activate the ILS frequencies when cleared for approach”	
WS	10:18:59	Aural landing gear configuration warning horn - on	Crew do not address and discuss the warning
WS	10:19:01	Aural landing gear configuration warning horn - off	Crew do not address and discuss the warning
PNF	10:19:02	“Reducing to two hundred twenty from 13 thousand, instructor"	

Continued on next page

Continuation of Table B.1

Agent	Time	Content	Remarks
ATCO	10:19:04	"Turkish 1-9-5-1, descend to two thousand, 1-0-2-7"	
PF	10:19:08	"Two thousand, 1-0-2-7, 1-9-5-1"	
PNF	10:19:17	"May I give level change, instructor?"	
		Sound of trim wheel moving	
PF	10:19:23	"OK"	
PF	10:19:25	"Are you going to reduce speed?"	
PNF	10:19:28	"I am going to reduce because we have not reached 13 miles yet"	
PF	10:19:40	"2-7 set"	
PNF	10:19:41	"1-0-2-7 set instructor"	
ATCO	10:19:42	"Turkish 1-9-5-1, turn left heading 2-6-5"	
PF	10:19:47	"Left 2-6-5, 1-9-5-1"	
PF	10:19:51	"Left 2-6-5"	
PNF	10:19:52	"2-6-5"	
PF	10:20:10	"F-M-S in" "Your FMS"	
PNF	10:20:13	[unclear]	
PF	10:20:18	"[unclear]You have the radio"	
PNF	10:20:21	"[unclear] What did you (he, she) say?"	
ATCO	10:20:22	"Turkish 1-9-5-1, good morning"	
PF	10:20:25	"Good morning, time is 3-0, we have [unclear] on board"	
ATCO	10:20:30	"Turkish 1-9-5-1, you may expect parking stand Golf 2"	
PF	10:20:34	"Thank you very much. See you next on the ground."	
PF	10:20:41	"Parking position same as covered before"	
PNF	10:20:42	"Ok, instructor"	
PNF	10:22:15	"Flaps 1, speed check"	
PNF	10:22:22	"Speed 1-9-5, instructor"	
ATCO	10:22:38	"Turkish 1-9-5-1, turn left heading 2-1-0, cleared approach, 1-8 Right"	

Continued on next page

Continuation of Table B.1

Agent	Time	Content	Remarks
PF	10:22:42	"Left 2-1-0, clear I-L-S, Turkish 1-9-5-1"	
PNF	10:22:47	"2-1-0 set, instructor"	
PNF	10:22:53	"Approach selected, instructor, second autopilot"	
WS	10:22:58	Autopilot disconnect horn (sounds for 4 seconds)	Crew do not address and discuss the warning
PNF	10:23:04	"Courses active, instructor"	
PNF	10:23:10	"Second autopilot engaged"	Crew's previous SA does not allow for communicating and reasoning behind A/P's disconnection
PF	10:23:12	"OK"	
PNF	10:23:13	"Engaged"	
PNF	10:23:30	"Flaps 5"	
?	10:23:32	[unclear]	
WS	10:23:43	Aural landing gear configuration warning - on	Crew do not address and discuss the warning
WS	10:23:48	Aural landing gear configuration warning - off	Crew do not address and discuss the warning
PNF	10:23:49	"[unclear] Flaps, gear down"	
PNF	10:23:50	"Flaps 15"	
PF	10:24:04	"Localizer alive"	
PNF	10:24:07	instructor	
PF	10:24:09	"Localizer capture"	No communication is made regarding the approach towards interception of glide slope and the necessary maneuvers
PNF	10:24:14	"Speed 1-4-0, setting set" (Unclear what this means)	
	10:24:19	Cabin chime	
ATCO	10:24:24	"Turkish 1-9-5-1, contact tower, 1-18-27, bye, bye"	PF does not share any information with PNF regarding the procedure the pilot is following
			Continued on next page

Continuation of Table B.1

Agent	**Time**	**Content**	**Remarks**
PF	10:24:27	"18-27 have a good day, sir"	It is unclear if the PNF is aware of the procedure to intercept the glide slope from above
SP	10:24:36	"We have radio altimeter failure, instructor"	No communication is made regarding possible consequences of the failure of LRRA-1
PF	10:24:38	"Ooookay"	No communication is made regarding the mode change of the A/T.
PF	10:24:44	"Amsterdam Tower, Turkish 1-9-5-1, 1-8-Right"	It is unclear if the crew failed at noticing the mode of the A/T, or if no monitoring of the PFD was conducted at all.
ATCO	10:24:48	"Turkish 1-9-5-1, good morning, runway 1-8-Right, cleared to land, winds 2-10 at 9"	
PF	10:24:52	"Cleared to land. Thank you."	
PNF	10:24:55	"Established altitude set"	
PF	10:25:04	"Thousand"	
PNF	10:25:06	"Check"	
PF	10:25:10	"Flaps 40"	
		Sound of flap lever being moved	
PNF	10:25:12	"Speed set"	
PF	10:25:17	"Yes, not in checklist completed"	
PF	10:25:19	"Speedbrake"	
PNF	10:25:20	"Speedbrake armed, green light"	
	10:25:21	2 clicks	
PF	10:25:26	"One, one, one"	
PNF	10:25:27	"Speedbrake armed, green light"	
PF	10:25:28	"Landing gear OK"	

Continued on next page

Continuation of Table B.1

Agent	Time	Content	Remarks
PNF	10:25:29	Gear down, please, three green”	
PF	10:25:31	“Flaps”	
PNF	10:25:32	“Flaps 40, green light”	
SP	10:25:33	“Cabin report confirmed”	
PNF	10:25:34	“Missed approach altitude set”	
PF	10:25:37	“Five hundred”	
PNF	10:25:38	“All lights on”	
PF	10:25:40	“Please warn the cabin crew”	
SP	10:25:42	“Ah-huh”	
PNF	10:25:44	“Cabin crew take your seats”	
WS	10:25:47	Stick shaker - on	Since the activation of the ’Retard Flare’ mode of the A/T, no communication is made regarding the decrease in airspeed, till the initiation of the stick shaker.
SP	10:25:49	“Speed, instructor"	
PF	10:25:49	“I Have”	
SP	10:25:51	“100 knots instructor!"	
SP	10:25:52	“Speed, instructor"	
WS		Autopilot disconnect aural warning tone	
WS	10:25:57	Stick shaker off	
WS	10:25:57	“Sink rate”	
WS	10:25:58	“Pull up, pull up”	
WS	10:25:59	Sticker shaker - on	
?	10:26:02	[unclear]	
-		End of recording	
			Concluded

C

INTRODUCTION TO AGENT-BASED MODELING

The operation of a commercial flight from point A to point B can be treated as a complex socio-technical operation. Considering the complexities in such an operation, an Agent-Based Modeling, ABM, approach is a promising approach to simulate the actions and interactions of the individual or collective entities involved in the operation (Blom and Sharpanskykh, 2014-2015). This appendix provides a short overview and introduction of ABM (Jaberi, 2016).

In terms of the definition of what can be labeled as an Agent, there is no universally accepted definition of the term in the context of Agent-Based Modeling and Simulation, ABMS (Macal and North, 2010). An agent may, however, be defined as anything that can be viewed as perceiving its environment through sensors, with the ability to act upon that environment through effectors (Russell and Norvig, 1995). Agents, can be in the form of humans, systems, or any other type of entity pursuing a certain goal (Blom and Sharpanskykh, 2014-2015). Agents must possess the ability to perceive their environment and act upon it when required. They do so through interactions with the surrounding environment and other agents. The ability to make decisions upon assessment of their situation also falls under the requirements for the definition of an agent (Blom and Sharpanskykh, 2014-2015).

In addition to a free interaction with their environment, interaction with other agents present in the surroundings often remains a general requirement for agents to achieve their goals. As such, Multi-Agent Systems are formed, MAS (Blom and Sharpanskykh, 2014-2015). An ABM approach focuses on modeling the system with the goal of analyzing agents' behavior and investigating if agents are obeying the rules assigned to them. An application of MAS enables understanding and prediction of emergence of safety-related issues, when studying and analyzing operations in the air transportation systems

(Blom and Sharpanskykh, 2014-2015). A multi-agent system approach can, however, be implemented using the Agent-Based Modeling approach (Getchell, 2008) (Niazi and Hussain, 2011). MAS has been proven to be a suitable paradigm to model the dynamics of complex socio-technical systems (Blom and Sharpanskykh, 2015) (Dignum, 2009).

When investigating the operation of an aviation flight, significant numbers of interactions between human operators, technical systems, control surfaces, regulations and procedures should be considered, occurring prior to and throughout the flight. Although proper functionality of operation-related elements can influence the safety of the operation significantly, the safety is also affected by the complexity of these interactions. Especially, in non-nominal conditions (Blom et al., 2003). As a measure to reduce this complexity while modeling the operation, an agent-based modeling of the system and the underlying elements can help clarify how these elements interact with each other and their environment. As such, the complexity of such an agent-based model will be determined based on the number of agents involved, their dynamic behaviors, interactions and inter-dependencies with other agents (Blom et al., 2003).

An Agent-Based Model can only be created once one has sufficient knowledge and understanding of the agents. As Shalizi (Shalizi, 2006) describes, an agent is a "persistent thing", of which some states are "worth representing" for the purpose of a specific analysis (Shalizi, 2006). To create an agent-based model, Shalizi considers an understanding of the following components as essential components; collection of agents, their states, the rules governing the interactions between the agents and the environment in which the agents act (Shalizi, 2006). A summary of a more detailed description of these components, as defined by Nikolic (Davis and Nikolic, 2015-2016), can be found in the literature research performed prior to this report (Jaberi, 2016).

The requirement for a successful analysis of the operation of Flight TK1951 will thus be the identification of elements involved in the unfolding of the sequence of events as they occurred on Flight TK1951. These elements will construct the agent-population of the ABM. This will assist in understanding and evaluating their awareness and interactions with their environment and other agents involved. It will thus be possible to examine the types of behavior these agents will exhibit when subjected to different technical or mental conditions. For the purpose of this report, the main focus is on the assessment of the human-agents acting and interacting with their system-agents. As such, the human-agent components of the ABM will be studied and their relations and interactions with other agents in the Flight TK1951 environment will be outlined. This will be next be coupled with the Contextual Control theory which is applied next. Further information on the application of the two theories is provided in Chapters 3 and 4. In order to assess the level of understanding and awareness of the agents with regards to own and other agents' states and performance rates, the concept of Situation Awareness in an MAS will be of a high value.

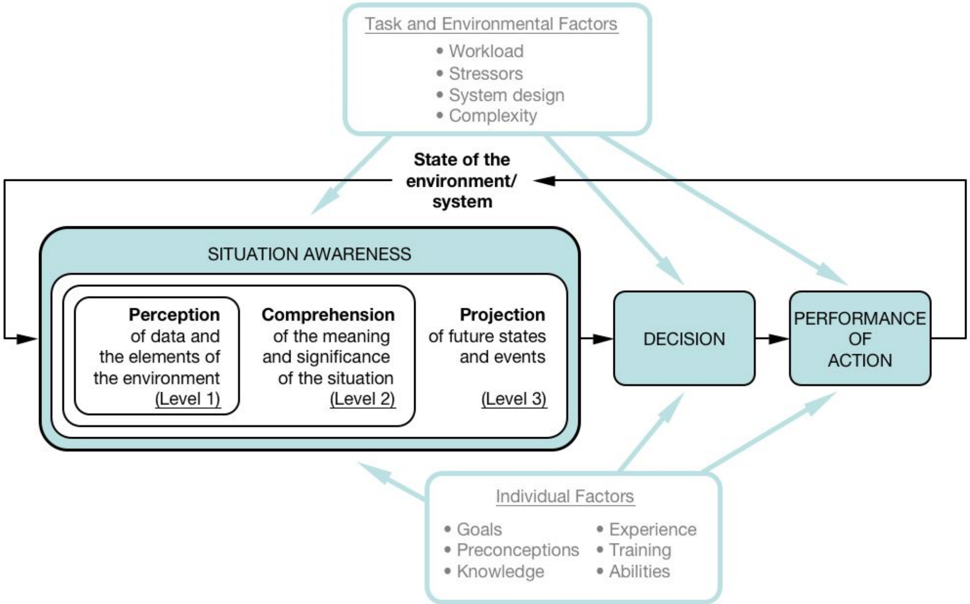

Figure C.1: Endsley's model of SA formation (Endsley, 1995)

C.1. SITUATION AWARENESS, SA

Introducing Situation Awareness, SA, in complex dynamic systems, Endsley (Endsley, 1995) considers SA as a crucial construct on which decision making and performance in such systems hinge (Endsley, 1995). Her definition of SA follows as:

"SA is the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status on the near future" (Endsley, 1995).

The SA is further described as the level of awareness that an individual, human or system component, has of a situation (Blom and Sharpanskykh, 2015). An agent within a system may possess a degree of SA, with regards to its own environment, the overall system goal and the other agents. While possessing a correct SA with respect to other agents and the surrounding environment is important, updating this SA is equally important. The process of achieving, acquiring and maintaining SA is referred to as the concept of Situation Assessment (Endsley, 1995), which is considered as a dynamic process (Endsley, 1995). Although deviations exist in the definition of an agent, the role played by SA in an ABM of complex socio-technical systems is considered as a key contributor (Macal and North, 2010) (Blom and Sharpanskykh, 2015).

The formation of SA in a Situation Assessment process is based on three stages, Perception, Comprehension, and Projection (Endsley, 1995), as an attempt to enable the agent in performing the required task for achieving the desired objective. Figure C.1 illustrates Endsley's three levels of SA formation (Endsley, 1995).

As it can be seen in Figure C.1, the formation of SA required by the agents to make decisions and to take actions, is completed through the three steps of perception, comprehension and projection. The model introduced by Endsley is based on human information processing theories (Blom and Sharpanskykh, 2015), and can be better understood through these three steps. The first step, at which the agent achieves the basic SA-1, is with regards to perceiving by the individual the state, attributes and dynamics of task-related elements in the surrounding environment. The second step, Comprehension, relates to the integration of recognition and evaluation of SA-1 elements, in order to understand how it will impact the objectives of the individual (Endsley, 1995) (Blom and Sharpanskykh, 2015). Finally, the highest level of SA is achieved at level 3, which involves the capability to project the future actions of the elements (Endsley, 1995) and to predict the future states of the systems and elements in the environment. For this, the current states of the elements are used (Blom and Sharpanskykh, 2015). This is achieved through extrapolating the knowledge of the states and dynamics of the elements and comprehension of the situation, achieved at levels one and two (Endsley, 1995). For instance, in the case of a pilot's situation assessment about his/her aircraft, the completion and development of SA-1, -2 and -3 come from the state of environment, experience and knowledge of the pilot, and the rules of flight dynamics, respectively (van Ettinger, 2013).

SA Error

In a complex MAS, while agents are continuously occupied with updating their relative SA, errors are inevitable. These will thus need to be studied, modeled and counter-acted, through comparison of current data with reference and new data, and subsequently updating the database.

With regards to the complex nature of air transport, the formation and presence of errors in SA needs to be fully understood, in order to properly implement these possible variations in the modeling of such an operation. In general, errors in SA may contribute significantly to an increased accident risk. These errors may be detailed in two perspectives, single-agent and multi-agent SA.

In regards to the situation assessment of a single human-agent, two types of erroneous SA can be defined (Endsley, 1995):

1. **Incomplete SA**
   knowledge of only some elements available, while no understanding and awareness of other elements' current or future state is available

2. **Inaccurate SA**
   erroneous knowledge in regards to the value/state of some elements within the system

Endsley presents such SA errors in three levels (Endsley, 1995):

- **Level 1**
  Person wrongly or not perceiving task-relevant information
- **Level 2**
  person wrongly interpreting perceived information
- **Level 3** person wrongly predicting a future status; for instance, due to the lack of a good mental model, memory limitations or work overload

Moving over to a complex MAS, where the outcome of the system depends on the various agents involved and their interactions, a larger degree of SA errors may emerge. This is mainly due to the interactions between the agents, through means of communication, interpretation or prediction (Endsley, 1995) (Blom et al., 2003). The underlying cause of such SA errors will be lack of or incomplete input of information from one agent into the other. The effect of such incomplete or erroneous SA's will be put into context when examining the SA of the flight crew of Flight TK1951, with regards to their faulty cockpit equipment and the consequences on the rest of the remainder of the systems aboard the aircraft. This is outlined in Chapters 3 and 5.

C.2. MULTI-AGENT SITUATION AWARENESS, MA-SA

As it was outlined earlier, a MAS approach best fits the study of a multi-agent operation such as a commercial flight. For this purpose, the framework of Multi-Agent SA (Blom and Sharpanskykh, 2015), MA-SA, can be used, which is based on multi-agent SA relations in a system composed of N agents $A_k, k = 1, ..., N$. It is inspired from the MA-SA model of Stroeve et. al. (Blom et al., 2003), which extends the model of Endsley to incorporate non-human agents in a multi-agent situation. The MA-SA approach also captures MA-SA relations and shared MA-SA between multiple human agents in such socio-technical systems.

The framework of MA-SA brings several extensions to Engsley's SA model. These include incorporation of non-human agents, the possibility for MA-SA relations between any two agents to be asymmetric, and allowing for any in-depth systematic capturing of SA of one agent about the SA of another agent (Blom and Sharpanskykh, 2015).

MA-SA considers a MAS consisting of N agents $A_k, k = 1, ..., N$. At each moment in time t, each agent A_k has state $x_{t,k}, k = 0, ..., N$. The state $x_{t,k}$ of agent A_k can consist of multiple state elements, with regards to own state, other agents or non-agent entities in the environment . The SA of agent A_k at time t about the state of agent A_j is denoted by $\sigma^j_{t,k}$, defining the set of states $x_{t,k}(s)$ of agent A_k for which there is a MA-SA relation with state elements of agent A_j (Blom and Sharpanskykh, 2015).

While further description of mathematical presentations of MA-SA relations can be found in the appropriate papers (Blom and Sharpanskykh, 2015) (Blom et al., 2003), a short summary of the components of $\sigma^j_{t,k}$ are outlined here (Blom et al., 2003). Given below is the composition of $\sigma^j_{t,k}$:

$$\sigma^j_{t,k} = \begin{array}{c}\text{SA of agent k}\\ \text{at time t about}\\ \text{agent j}\end{array} = \begin{pmatrix}\text{Identity}^j_{t,k}\\ \text{State}^j_{t,k}\\ \text{Mode}^j_{t,k}\\ \text{Intent}^j_{t,k}\end{pmatrix} \tag{C.1}$$

where $\sigma^j_{t,k}$ represents the SA of agent k with regards to agent j, at time t. As it can be seen in Equation C.1, the SA vector consists of four components; namely, Identity, State, Mode and Intent. In regards to the human agents acting during Flight TK1951, upon a full and correct SA of the crew k with regards to its system component j, this provides the crew member with two groups of information. The first, the State SA, consists of the identity, state and current mode of the component, by which the crew can fully understand and relate to the information regarding the state of the component. Any faulty behavior of the component, given a correct and up-to-date SA of the crew member, will be recognized at this point. The last item of σ, namely the Intent of agent j, relates to the expectations by the crew member of the system component, based on his/her current understanding of the design and behavior rules of the system component.

Further application of the ABM theory with regards to Flight TK1951 can be found in Chapter 3.

D

Representation of Additional Simulation Results

This appendix presents additional results regarding the development of PF's taskload vector throughout the flight. Table D.1 provides a detailed representation of the development of the taskload density according to the reference event sequence of the reference scenario. Next, Figures D.1 to D.3 provide comparisons of the development of the taskload densities in between the reference scenario and the three scenario variants.

Remark:
Throughout Table D.1, any range in time in which the taskload density does remains at a minimum value of zero consecutive tasks, the range in time is indicated using (**...**) in between the starting and ending time in *seconds*. This is done in order to shorten the representation of the taskload vector for the entire flight.

Table D.1: Reference Scenario; formation of complete PF's taskload array, and control modes at different stress thresholds

Time [s]	Originating Task #	TL and corresponding CM, at				TL and CM at 2x Speed, at		
		T.L.	TH: 3	TH: 4	TH: 5	TH: 3	TH: 4	TH: 5
0	1	1				1	1	1
1	-	1				1	1	1
2	-	1				1	1	1
3	-	1				1	1	1
4	-	1				1	1	1
5	-	1				1	1	1
6	-	1				1	1	1
7	-	1				1	1	1
8	-	1				1	1	1
9	-	1				1	1	1
10	-	1				1	1	1
11	-	1				1	1	1
12	-	1				1	1	1
13	-	1				1	1	1
14	-	1				1	1	1
15	-	1				1	1	1
16	-	1				1	1	1
17	-	1				1	1	1
18	-	1				1	1	1
19	-	1				1	1	1
20	2	1				1	1	1
21	-	1				1	1	1
22	-	0				0	0	0
23	-	0				0	0	0
24	-	0				0	0	0
25	-	0				0	0	0
26	-	0				0	0	0
...	-	0				0	0	0
710	-	0				0	0	0
711	-	0				0	0	0
712	-	0				0	0	0
713	-	0				0	0	0
714	-	0				0	0	0
715	-	0				0	0	0
716	-	0				0	0	0
717	-	0				0	0	0

Continued on next page

Continuation of Table D.1

Time [s]	Originating Task #	TL and corresponding CM, at				TL and CM at 2x Speed, at		
		T.L.	TH: 3	TH: 4	TH: 5	TH: 3	TH: 4	TH: 5
718	-	0				0	0	0
719	7-9	3				3	3	3
720	-	3				2	3	3
721	-	2				2	2	2
722	-	2				1	2	2
723	-	2				1	2	2
724	-	2				0	2	2
725	-	1				0	1	1
726	-	1				0	1	1
727	-	0				0	0	0
728	-	0				0	0	0
729	-	0				0	0	0
730	-	0				0	0	0
731	10-12	3				3	3	3
732	-	3				2	3	3
733	-	2				2	2	2
734	-	2				1	2	2
735	-	2				1	2	2
736	-	2				0	2	2
737	-	1				0	1	1
738	-	1				0	1	1
739	-	0				0	0	0
740	-	0				0	0	0
...	-	0				0	0	0
836	-	0				0	0	0
837	-	0				0	0	0
838	-	0				0	0	0
839	-	0				0	0	0
840	-	0				0	0	0
841	-	0				0	0	0
842	-	0				0	0	0
843	-	0				0	0	0
844	13-15	3				3	3	3
845	-	3				2	3	3
846	-	2				2	2	2
847	-	2				1	2	2
848	-	2				1	2	2

Continued on next page

Continuation of Table D.1

Time [s]	Originating Task #	TL and corresponding CM, at				TL and CM at 2x Speed, at		
		T.L.	TH: 3	TH: 4	TH: 5	TH: 3	TH: 4	TH: 5
849	-	2				0	2	2
850	-	1				0	1	1
851	-	1				0	1	1
852	-	0				0	0	0
853	-	0				0	0	0
854	-	0				0	0	0
855	-	0				0	0	0
856	-	0				0	0	0
857	-	0				0	0	0
858	-	0				0	0	0
859	-	0				0	0	0
860	-	0				0	0	0
...	-	0				0	0	0
946	-	0				0	0	0
947	-	0				0	0	0
948	-	0				0	0	0
949	-	0				0	0	0
950	-	0				0	0	0
951	-	0				0	0	0
952	16-18	3				3	3	3
953	-	3				2	3	3
954	-	2				2	2	2
955	-	2				1	2	2
956	-	2				1	2	2
957	-	2				0	2	2
958	-	1				0	1	1
959	-	1				0	1	1
960	-	0				0	0	0
961	-	0				0	0	0
962	-	0				0	0	0
963	-	0				0	0	0
964	-	0				0	0	0
965	-	0				0	0	0
...	-	0				0	0	0
1126	-	0				0	0	0
1127	-	0				0	0	0
1128	-	0				0	0	0

Continued on next page

Continuation of Table D.1

Time [s]	Originating Task #	TL and corresponding CM, at				TL and CM at 2x Speed, at		
		T.L.	TH: 3	TH: 4	TH: 5	TH: 3	TH: 4	TH: 5
1129	-	0				0	0	0
1130	-	0				0	0	0
1131	-	0				0	0	0
1132	-	0				0	0	0
1133	19	1				1	1	1
1134	-	0				0	0	0
1135	-	0				0	0	0
1136	-	0				0	0	0
1137	-	0				0	0	0
1138	-	0				0	0	0
1139	-	0				0	0	0
1140	-	0				0	0	0
1141	-	0				0	0	0
1142	-	0				0	0	0
1143	-	0				0	0	0
1144	-	0				0	0	0
1145	-	0				0	0	0
1146	-	0				0	0	0
1147	-	0				0	0	0
1148	-	0				0	0	0
1149	-	0				0	0	0
1150	20-22	3				3	3	3
1151	-	2				2	2	2
1152	-	2				1	2	2
1153	-	1				1	1	1
1154	-	1				0	1	1
1155	-	0				0	0	0
1156	-	0				0	0	0
1157	-	0				0	0	0
1158	-	0				0	0	0
1159	-	0				0	0	0
1160	-	0				0	0	0
1161	-	0				0	0	0
1162	-	0				0	0	0
1163	-	0				0	0	0
1164	-	0				0	0	0
1165	-	0				0	0	0
1166	-	0				0	0	0

Continued on next page

Continuation of Table D.1

Time [s]	Originating Task #	TL and corresponding CM, at				TL and CM at 2x Speed, at		
		T.L.	TH: 3	TH: 4	TH: 5	TH: 3	TH: 4	TH: 5
1167	-	0				0	0	0
1168	-	0				0	0	0
1169	-	0				0	0	0
1170	-	0				0	0	0
1171	23-24	2				2	2	2
1172	-	1				1	1	1
1173	-	1				1	1	1
1174	-	0				0	0	0
1175	-	0				0	0	0
1176	-	0				0	0	0
1177	-	0				0	0	0
1178	-	0				0	0	0
1179	-	0				0	0	0
1180	-	0				0	0	0
1181	-	0				0	0	0
1182	-	0				0	0	0
1183	-	0				0	0	0
1184	-	0				0	0	0
1185	-	0				0	0	0
1186	25-27	3				3	3	3
1187	-	3				2	3	3
1188	-	2				1	2	2
1189	-	2				1	2	2
1190	28	2				2	2	2
1191	-	2				2	2	2
1192	29	3				2	3	3
1193	-	3				2	3	3
1194	-	2				1	2	2
1195	-	2				1	2	2
1196	-	1				0	1	1
1197	-	1				0	1	1
1198	-	0				0	0	0
1199	-	0				0	0	0
1200	-	0				0	0	0
1201	-	0				0	0	0
1202	-	0				0	0	0
1203	-	0				0	0	0
1204	-	0				0	0	0

Continued on next page

Continuation of Table D.1

Time [s]	Originating Task #	TL and corresponding CM, at				TL and CM at 2x Speed, at		
		T.L.	TH: 3	TH: 4	TH: 5	TH: 3	TH: 4	TH: 5
1205	-	0				0	0	0
1206	-	0				0	0	0
1207	-	0				0	0	0
1208	-	0				0	0	0
1209	-	0				0	0	0
1210	-	0				0	0	0
1211	-	0				0	0	0
1212	-	0				0	0	0
1213	-	0				0	0	0
1214	-	0				0	0	0
1215	30	1				1	1	1
1216	-	1				1	1	1
1217	-	0				0	0	0
1218	-	0				0	0	0
1219	-	0				0	0	0
1220	-	0				0	0	0
1221	-	0				0	0	0
1222	-	0				0	0	0
1223	-	0				0	0	0
1224	-	0				0	0	0
1225	31-32	2				2	2	2
1226	-	2				2	2	2
1227	-	1				1	1	1
1228	-	1				1	1	1
1229	-	0				0	0	0
1230	-	0				0	0	0
1231	-	0				0	0	0
1232	-	0				0	0	0
1233	-	0				0	0	0
1234	-	0				0	0	0
1235	-	0				0	0	0
1236	33-35	3				3	3	3
1237	-	3				2	3	3
1238	-	2				2	2	2
1239	-	2				1	2	2
1240	-	2				1	2	2
1241	-	2				0	2	2
1242	36-38	4				3	4	4

Continued on next page

Continuation of Table D.1

Time [s]	Originating Task #	TL and corresponding CM, at				TL and CM at 2x Speed, at		
		T.L.	TH: 3	TH: 4	TH: 5	TH: 3	TH: 4	TH: 5
1243	-	4				2	3	4
1244	-	3				1	2	3
1245	-	3				1	2	3
1246	-	2				1	1	2
1247	-	2				0	1	2
1248	-	1				0	1	1
1249	-	1				0	0	1
1250	-	1				0	0	1
1251	-	0				0	0	0
1252	-	0				0	0	0
1253	-	0				0	0	0
1254	-	0				0	0	0
1255	-	0				0	0	0
1256	-	0				0	0	0
1257	39	1				1	1	1
1258	-	0				0	0	0
1259	-	0				0	0	0
1260	-	0				0	0	0
1261	-	0				0	0	0
1262	40-48	9				9	9	9
1263	-	9				8	8	8
1264	-	8				7	7	7
1265	-	8				6	6	6
1266	-	7				5	5	5
1267	-	7				4	4	4
1268	-	6				4	4	4
1269	-	5				3	3	3
1270	49-50	7				5	5	5
1271	-	6				4	4	5
1272	-	6				3	3	4
1273	-	6				3	3	3
1274	-	5				2	2	3
1275	-	5				2	2	3
1276	51-56	11				7	8	9
1277	57	11				7	8	9
1278	58	12				7	8	10
1279	-	11				6	7	9
1280	-	11				5	6	8

Continued on next page

Continuation of Table D.1

Time [s]	Originating Task #	TL and corresponding CM, at				TL and CM at 2x Speed, at		
		T.L.	TH: 3	TH: 4	TH: 5	TH: 3	TH: 4	TH: 5
1281	-	11				5	5	7
1282	-	11				4	5	6
1283	-	10				3	4	5
1284	-	10				3	3	5
1285	-	10				2	3	4
1286	-	9				1	2	3
1287	-	9				1	1	3
1288	-	8				0	1	3
1289	-	8				0	0	2
1290	-	7				0	0	1
1291	-	7				0	0	1
1292	-	6				0	0	0
1293	-	6				0	0	0
1294	-	5				0	0	0
1295	-	5				0	0	0
1296	-	5				0	0	0
1297	-	4				0	0	0
1298	-	4				0	0	0
1299	59-60	5				2	2	2
1300	-	5				1	1	1
1301	61	6				1	1	1
1302	-	5				0	0	0
1303	-	4				0	0	0
1304	-	4				0	0	0
1305	-	3				0	0	0
1306	-	3				0	0	0
1307	63-64	4				2	2	2
1308	-	4				1	1	1
1309	-	3				0	0	1
1310	64-66	5				3	3	3
1311	-	4				2	3	3
1312	-	4				2	2	2
1313	-	3				1	2	2
1314	-	3				1	2	2
1315		2				0	1	1
1316		2				0	1	1
1317		2				0	1	1
1318		1				0	0	0

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Continuation of Table D.1

Time [s]	Originating Task #	TL and corresponding CM, at				TL and CM at 2x Speed, at		
		T.L.	TH: 3	TH: 4	TH: 5	TH: 3	TH: 4	TH: 5
1319		1				0	0	0
1320		1				0	0	0
1321		0				0	0	0
1322		0				0	0	0
1323		0				0	0	0
1324		0				0	0	0
1325	-	0				0	0	0
1326	-	0				0	0	0
1327	-	0				0	0	0
1328	-	0				0	0	0
1329	-	0				0	0	0
1330	-	0				0	0	0
1331	-	0				0	0	0
1332	-	0				0	0	0
1333	-	0				0	0	0
1334	-	0				0	0	0
1335	-	0				0	0	0
1336	-	0				0	0	0
1337	-	0				0	0	0
1338	-	0				0	0	0
1339	-	0				0	0	0
1340	-	0				0	0	0
1341	-	0				0	0	0
1342	-	0				0	0	0
1343	-	0				0	0	0
1344	-	0				0	0	0
1345	-	0				0	0	0
1346	-	0				0	0	0
1347	-	0				0	0	0
1348	-	0				0	0	0
1349	-	0				0	0	0
1350	67	1				1	1	1
1351		1				1	1	1
1352		0				0	0	0
1353		0				0	0	0
1354	68-70	3				3	3	3
1355		3				2	3	3
1356		2				1	2	2

Continued on next page

Continuation of Table D.1

Time [s]	**Originating Task #**	**TL and corresponding CM, at**				**TL and CM at 2x Speed, at**		
		T.L.	**TH: 3**	**TH: 4**	**TH: 5**	**TH: 3**	**TH: 4**	**TH: 5**
1357		2				0	2	2
1358		1				0	1	1
1359		1				0	1	1
1360		0				0	0	0
1361	-	0				0	0	0
1362	-	0				0	0	0
1363	-	0				0	0	0
1364	-	0				0	0	0
1365	-	0				0	0	0
1366	-	0				0	0	0
1367	-	0				0	0	0
1368	-	0				0	0	0
1369	-	0				0	0	0
1370	-	0				0	0	0

Concluded

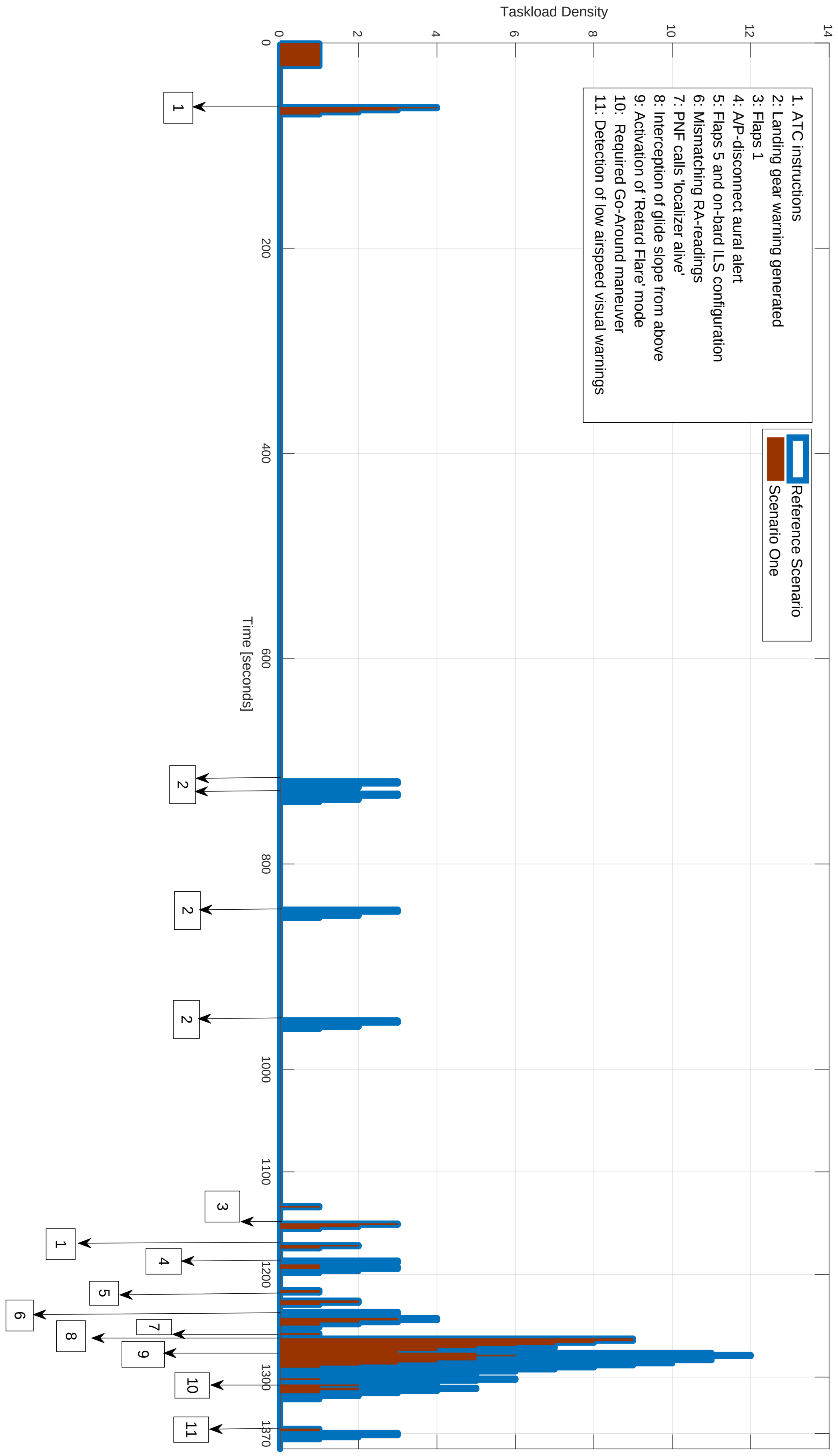

Figure D.1: PF's taskload vector; Reference Scenario vs Scenario One

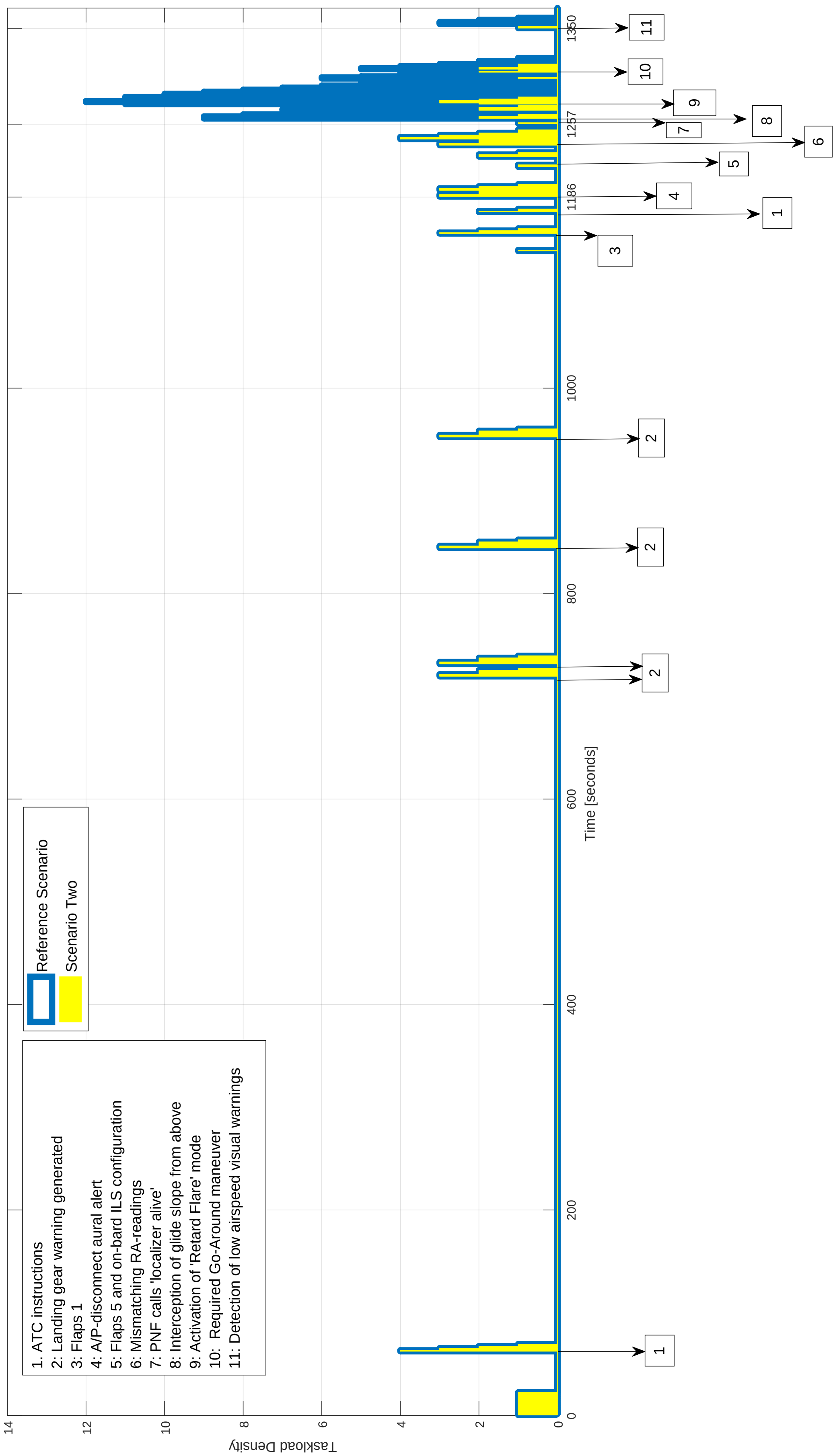

Figure D.2: PF's taskload vector; Reference Scenario vs Scenario Two

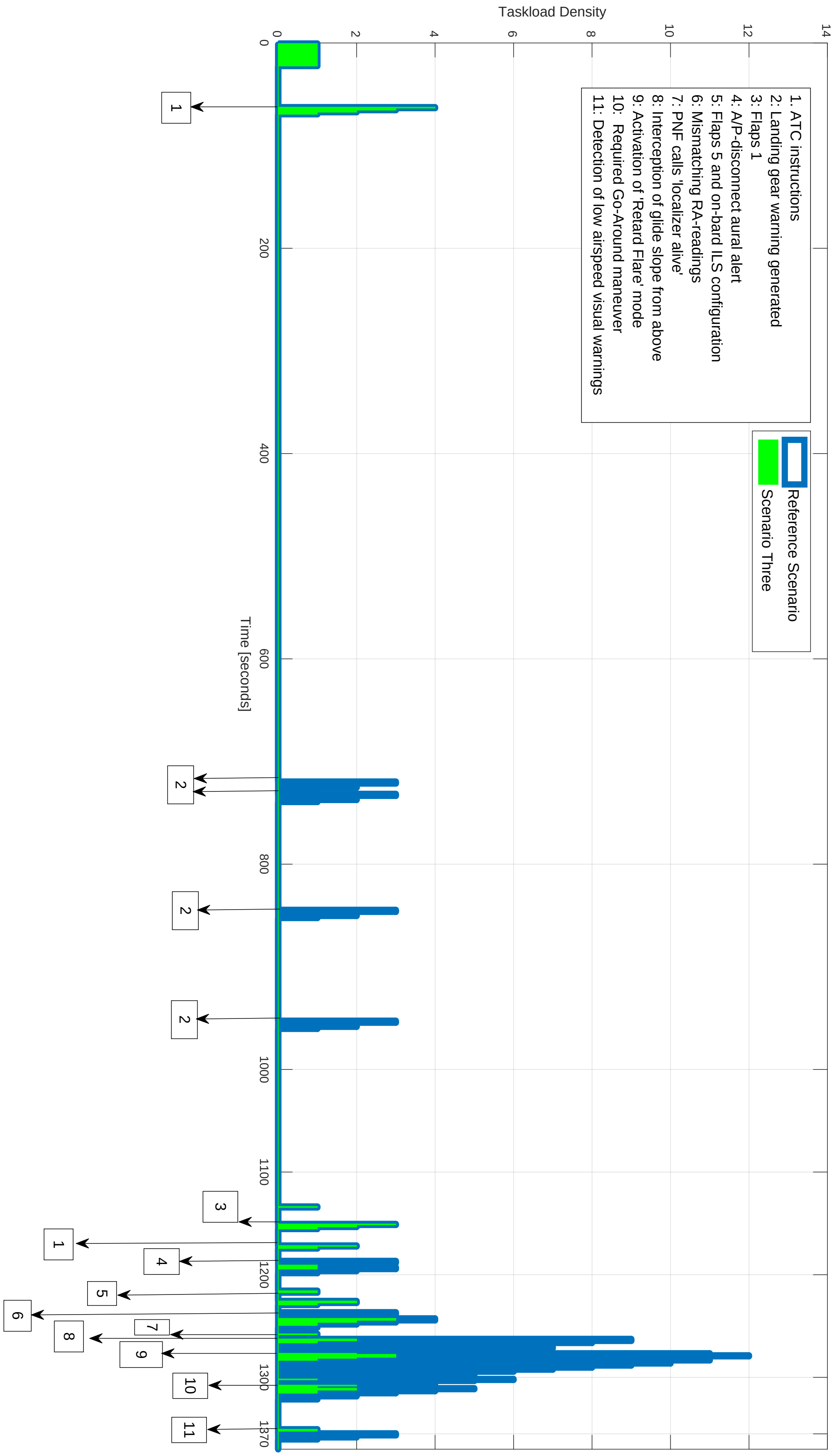

Figure D.3: PF's taskload vector; Reference Scenario vs Scenario Three