Test report large scale simulations

S. Hourlier (Thales), M. Wies (DLR), B. Kirwan (EUROCONTROL), V. Arrigoni, D. Ruscio (Deep Blue), T. Bos, F. Mohrmann (NLR), N. Maille (ONERA), J.M. André, T. Letouzé (IPB/ENSC), J. Diaz Pineda, C. Dormoy (CATIE), R. Charles, J. Nixon (Cranfield University)

Short abstract: Future Sky Safety is a Joint Research Programme (JRP) on Safety, initiated by EREA, the association of European Research Establishments in Aeronautics. The Programme contains two streams of activities: 1) coordination of the safety research programmes of the EREA institutes and 2) collaborative research projects on European safety priorities.

This deliverable is produced by the Project P6 “Human Performance Envelope” of Future Sky Safety. The main objective is to report the results of the second simulator experiments.

Programme Manager	Michel Piers, NLR
Operations Manager	Lennaert Speijker, NLR
Project Manager (P6)	Matthias Wies, DLR
Grant Agreement No.	640597
Document Identification	D6.6
Status	Approved
Version	2.0
Classification	Public

This page is intentionally left blank

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

Contributing partners

Company	Name
TAV	Sylvain Hourlier
DLR	Matthias Wies
ECTL	Barry Kirwan
DBL	Vanessa Arrigoni, Daniele Ruscio
NLR	Tanja Bos, Frederik Mohrmann
ONERA	Nicolas Maille
CSEM	Alia Lemkaddem, Olivier Grossenbacher
IPB/ENSC	Jean-Marc André, Théodore Letouzé
CATIE	Jaime Diaz Pineda, Charles Dormoy
CRANFIELD UNIVERSITY	Rebecca Charles, Jim Nixon

Document Change Log

Version	Issue Date	Remarks
1.0	25-12-2018	First formal release
2.0	28-12-2018	Second formal release

Approval status

Prepared by: *(name)*	**Company**	**Role**	**Date**
Sylvain Hourlier	TAV	Main Author	17-12-2018
Checked by: *(name)*	**Company**	**Role**	**Date**
Alex Rutten	NLR	Quality Assurance	28-12-2018
Approved by: *(name)*	**Company**	**Role**	**Date**
Matthias Wies	DLR	Project Manager (P6)	25-12-2018
Lennaert Speijker	NLR	Operations Manager	28-12-2018

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

Acronyms

Acronym	Definition
AC	Alternate Current
ACARE	Advisory Council for Aeronautics Research in Europe
ANOVA	Analysis Of Variance
AOI	Areas Of Interest
AP	Autopilot
ATC	Air Traffic Control
ATIS	Automatic Terminal Information Service
CAT	Category
CPT	Captain
DH	Decision Height
DME	Distance Measuring Equipment
EASp	European Aviation Safety plan
ECAM	Electronic Centralized Aircraft Monitoring
EFP	Electronic Flight Bag
ELEC	Electric
EREA	Association of European Research Establishments in Aeronautics
FAC	Flight Augmentation Computer
FCU	Flight Control Unit
FMA	Flight Mode Annunciator
FMC	Flight Management Computer
FO	First Officer
GEN	Generator
HF	Human Factors
HMI	Human Machine Interface
HPE	Human Performance Envelope
Hz	Hertz
ILS	Instrument Landing System
INOP	Inoperative
LAPA	Landin Performance

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

LFT	Left
MERIA	Mental Representation Impact Analysis
MR	Mental Representation
NASA TLX	NASA Task Load Index
NAV	Navigation
ND	Navigation Display
NM	Nautical Miles
OM	Operations Manual
PF	Pilot Flying
PFD	Primary Flight Display
PM	Pilot Monitoring
PPL	Private Pilot License
PSDM	Problem Solving and Decision Making
QRH	Quick Reference Handbook
RGT	Right
RWY	Runway
SA	Situation Awareness
SACL	Stress Arousal Checklist
SART	Situation Awareness Rating Technique
SD	Standard Deviation
SD	Situation Display
SME	Subject-Matter Expert
SMI	SensoMotoric Instruments
SRIA	Strategic Research and Innovation Agenda
SVS	Synthetic Vision System
VOR	Very High Frequency Omnidirectional Radio Range
WSHLD	Windshield

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

EXECUTIVE SUMMARY

Problem Area

Aviation accidents inevitably involve the pilot and are often ascribed to 'human error'. Human Factors studies over decades have focused on a number of causes of 'pilot error', from communication problems to fatigue to loss of situation awareness, in an attempt to stop pilot error and thus accidents. However, this 'single-shot' approach only gets us so far. To achieve a significant step change in avoiding or recovering from human error, we need to consider the full range of factors that can affect performance, and be able to detect when one or more are moving out of 'tolerance' zone.

In particular, to cope with the increased complexity in the cockpit, it is important to reduce the pilot cognitive demand, e.g. through an appropriate use of HMI (human-machine interface) support. The focus should be on the availability of resources (workload factor), with the design of HMI that enables pilots to be in a situation where they have sufficient cognitive resources to perform efficiently and safely their tasks. It is in the interest of safety to know when the limits of the human performance are reached.

The concept of Human Performance Envelope (HPE) was introduced and defined in the first deliverable (D6.1): "Concept for Human Performance Envelope" of FSS Project P6 "Human Performance Envelope". Real time simulations are performed, where the different HPE factors are manipulated in order to provoke a slow degradation of pilots` performance. To test the HPE concept, a real-time simulation with 10 First Officers from a major European airline was conducted at a DLR research full-scope, moving flight simulator in May, 2016. There is now a need to measure the impact of different HMIs on HPE and pilots' performances, through additional simulations providing data to be used to generate future solutions.

Description of Work

The objective of the second experiments is to evaluate the impact of the new Human Machine Interfaces (HMI) on pilot's performance and HPE. The experiments are conducted in the Avionics 2020 simulator at Thales in Bordeaux. Twenty pilots are invited to participate. The pilots fly the same scenario 2 that was used in the first experiments. This allows a comparison of the different HMIs in the two experiments. Several measures are applied during the experiments to evaluate the HPE state of the pilots and the effectiveness of the new HMI. In this deliverable, the results of the second large-scale flight simulation experiments are reported. These experiments are carried out to validate the new HMIs that were previously developed within the project P6 Human Performance Envelope of Future Sky Safety.

Results & Conclusions

Overall, there are three different steps with three different HMI that are evaluated in the two experiments performed in the Project P6 Human Performance Envelope of Future Sky Safety. Step 1 represents the first experiments in an A320 full flight simulator at DLR in Braunschweig with the normal HMI of an A320. Step 2 represents the second experiments at Thales in Bordeaux in the Avionics 2020 simulator with the basic HMI of the Avionics 2020 cockpit. Step 3 represents as well the second

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

experiments, but with the advanced HMI developed within the Project P6. Step 1 is used to determine the HPE state of the pilots and the difficulties they have in the scenario. Based on the results of these first experiments, the new HMI are developed. Step 2 is used to determine the differences between the A320 and the Avionics 2020 cockpit. Finally, step 3 is used to validate the new HMI by comparing it to step 1 and step 2. The results of the recorded various data reveals many difficulties pilots have when handling technical failures in a complex situation (results of step 1 and 2). The new HMI are designed to provide the required support to the pilots in these situations. The conducted validation experiments (step 3) are able to show a clear improvement of the pilots HPE when using the new HMI. Especially, elements of the mental representation like situation awareness are highly improved.

Applicability

The newly developed HMI is perceived to potentially improve pilot's performance and executive functions, by easing the HPE factors related to the piloting and monitoring tasks. The results provide usable insights for the design of new HMIs and particularly in critical and complex situations where the pilots need additional support to be able to maintain the required level of safety.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

This page is intentionally left blank

TABLE OF CONTENTS

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

LIST OF FIGURES

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

Future Sky Safety has received funding from the EU’s Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

LIST OF TABLES

1 INTRODUCTION

1.1. The Programme

The European Council Flightpath 2050 vision aims to achieve the highest levels of safety to ensure that passengers and freight as well as the air transport system and its infrastructure are protected. Trends in safety performance over the last decade indicate that the Advisory Council for Aeronautics Research in Europe (ACARE) Vision 2020 safety goal of an 80% reduction of the accident rate is not being achieved. A stronger focus on safety is required.

Future Sky Safety, established under coordination of EREA (Association of European Research Establishments in Aeronautics), is a transport research programme built on European safety priorities that brings together thirty-three European partners to develop new tools and new approaches to aviation safety. The programme links the EASp (European Aviation Safety plan) main pillars (operational issues, systemic issues, human performance and emerging issues) to the Flightpath 2050 safety challenges through four themes:

- **Theme 1** (new solutions for today's accidents) aims for breakthrough research to address the current main accident categories in commercial air transport with the purpose of enabling a direct, specific, significant risk reduction in the medium term.
- **Theme 2** (strengthening the capability to manage risk) conducts research on processes and technologies to enable the aviation system actors to achieve near-total control over the safety risk in the air transport system.
- **Theme 3** (building ultra-resilient systems, organizations and operators) conducts research on the improvement of systems, organisations and the human operator with the specific aim to improve safety performance under unanticipated circumstances.
- **Theme 4** (building ultra-resilient vehicles) aims at reducing the effect of external hazards on vehicle integrity as well as reducing the number of fatalities in case of accidents.

Together, these themes and the institutionally funded safety research intend to cover the safety priorities of Flight Path 2050 as well as the ACARE Strategic Research and Innovation Agenda (SRIA) (in particular the challenges brought forward by ACARE Working Group 4 "Safety and Security"). The programme will also help coordinate the research and innovation agendas of several countries and institutions.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

1.2. Project context

Future Sky Safety P6 addresses theme 3 (building ultra-resilient systems and operators) focussed on strengthening the resilience to deal with current and new risks of the humans and the organizations operating the air transport system.

P6 builds on a concept previously proposed in the air traffic management domain, extending it to the human operators in the cockpit. The aim of the project is to define and apply the Human Performance Envelope for cockpit operations and design, and determining methods to recover crew's performance to the centre of the envelope, and consequently to augment this envelope.

The HPE is to some extent a new paradigm in Human Factors. Rather than focusing on one or two individual factors for example situation awareness or fatigue, the HPE considers a range of common factors in accidents and maps how they work alone or in combination to lead to a performance decrement that could affect safety. The safe region on the envelope is defined by human performance concepts, which can be signalled and measured, allowing the pilots to detect and recover, or enabling external agencies to prompt recovery, or allowing automation to kick in and take over.

1.3. Objectives

The objectives of the project P6 of Future Sky Safety are to define the Human Performance Envelope, to conduct preliminary experiments in order to select and assess sensors for measuring the Human Performance Envelope, to conduct first flight simulator experiments in order to validate the Human Performance Envelope, to validate the sensors and to identify performance decrement limits of the pilots, to develop new Human Machine Interfaces in order to recover the performance of the pilots, and finally to conduct second flight simulator experiments in order to validate the new Human Machine Interfaces.

This report presents the results of the second flight simulator experiments.

1.4. Structure of the document

This document is divided into two sections, represented by chapter 2 and 3. Chapter 2 will describe and discuss the results of the second real time simulations in the Avionics 2020 simulator at Thales. Thereafter, Chapter 3 will provide a final conclusion about the results.

The validation plan, including a description of the scenario and of the measurements used, has already been described in D6.5 “Test plan large scale simulations with evaluation protocol”. Therefore, this will only be briefly described in this report again at the beginning of chapter 2.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

2 RESULTS OF THE SECOND LARGE SCALE SIMULATIONS

2.1. Summary of hypothesis

This deliverable reports the results of the second simulator experiments. The objective of these experiments is to evaluate the impact of the new HMI on pilot's performance and HPE.

The following general hypotheses have been formulated (Table 1).

Table 1: Hypothesis

Hypothesis 1	
H0	The Step 2 environment does not improve pilots' global HPE compared to Step 1
H1	The Step 2 environment improves pilots' global HPE compared to Step 1
Evaluation criterion: the average levels of the three HPE factors (workload, stress, and situation awareness) assessed during Step 2 are better compared with the results of Step 1.	

Hypothesis 2	
H0	The Step 3 environment does not improve pilots' global HPE and performance respect to Step 2
H1	The Step 3 environment improves pilots' global HPE and performance compared to Step 2
Evaluation criterion 1: The average levels of the three HPE factors (workload, stress, and situation awareness) assessed during Step 3 are better compared with the results of Step 2. **Evaluation criterion 2**: The average pilots' performance measured during Step 3 is better compared with the results of Step 2.	

Hypothesis 3	
H0	Enhanced mental representations will not improve pilots' awareness about operational consequences of technical limitations in critical situations
H1	Enhanced mental representations will improve pilots' awareness about operational consequences of technical limitations in critical situations
Evaluation criterion: Mental representation, Benefit Questionnaire and pilot performance are improved between Step 1 and 2, and between Step 2 and 3.	

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

2.2. Summary of measurements

The following measurements were taken:

- Demographic
- HPE factors
  - NASA TLX
  - SART
  - SACL
  - Samn-Perelli
- Video and voice recording
- Simulator data
- Physiological
  - Heart rate
  - Heart rate variability
  - Breath rate
  - Pupil diameter
  - Blink rate
- Eye-tracking
  - Point of gaze
  - Areas of interest
- Performance
  - Performance curves
  - Crew Competency Evaluation
  - Cognitive walkthrough
- Benefits questionnaire
  - Usability of HMI
  - Willingness to use HMI
  - Impact on cognitive load and executive functions

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

2.3. Simulator

The means used for the Step 2 and Step 3 evaluations is the cockpit demonstrator located at the Thales Campus in Merignac (Figure 1 and Figure 2). The flight model is taken from X-Plane simulator A320 and some add-on functionalities. The scenery is taken from Prepared 3D (Lockheed Martin) simulator. The aircraft is piloted with sidesticks, no rudder pedals. This simulator is used as demonstrator in Thales Campus and as tests bench and validation simulator.

The cockpit interface is composed of four 17'' touchscreens that represent the current state of Thales product line for cockpits. A Flight Control Unit (FCU) similar to what is available in an A320 is also available above the touchscreens to manage the flight parameters of the autopilot (altitude, speed, heading, etc.). In Figure 1 and Figure 2 we can see the cockpit of the Avionics 2020.

Figure 1: Cockpit of the Avionics 2020 simulator

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

Figure 2: The evaluation in the cockpit demonstrator

Each pilot has a Primary Flight Display (PFD). There is a central display, which is the Navigation Display (ND) shared by the two pilots. Below the ND there is the ECAM (Electronic Centralized Aircraft Monitoring).

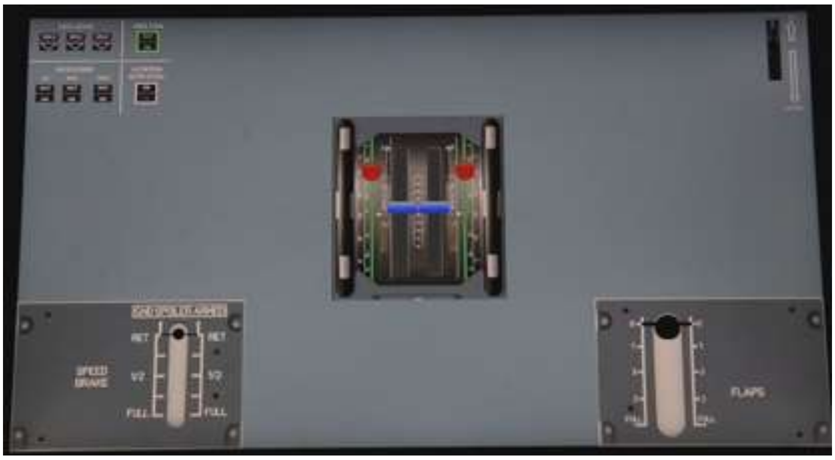


Figure 3: The Flight Control Unit used in the step 2 and step 3

And below the ECAM there is a touch screen which represents the pedestal with the throttle, the gear, the flaps and the speed brake levers (Figure 3). The pilots can select also the autobrake performance (Low, Medium, Max). And there are the feedback lights of the landing gear.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

2.4. Summary of scenario

The same scenario 2 as in the first simulator experiments was flown again in the second simulator experiments. This is a summary of the events:

- Approaching Bremen with standard fuel for 50 min remaining flight time
- Preparation of CAT1 approach RWY 27
- Go-around during ILS approach RWY 27 due to traffic on the RWY
- During turn into downwind ELEC AC BUS 1 FAULT
- Slight weather change with wind shift
- Captain forgets to activate climb mode
- Handling of ECAM procedure
- Decision were to land
- LAPA RWY 27
- Low on fuel emergency
- LAPA RWY 09
- OM-B expanded checklist and checking of QRH
- CAT2 ILS approach RWY 09
- Ice on window of captain on short final
- Manual landing of first officer

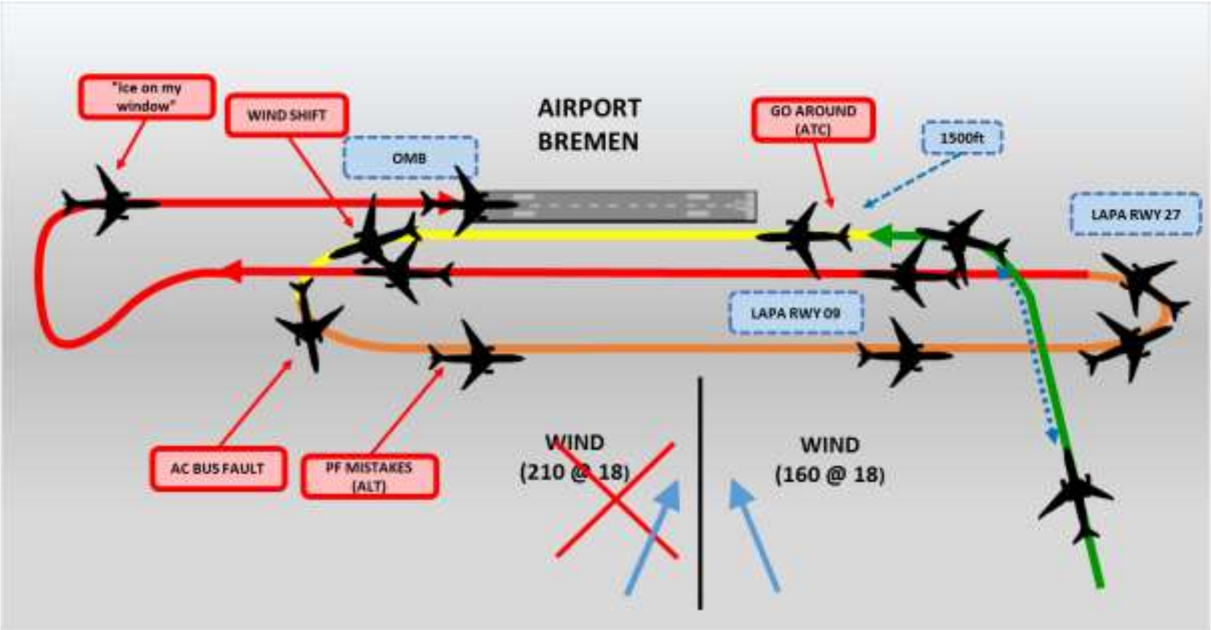


Figure 4: Overview of scenario 2

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

2.5. Description of interfaces

2.5.1. STEP 2 Interface description

Here is a description of the HMIs of Step 2 of the AV2020 that change compared to Step 1 A320.

Primary Flight Display PFD

In Figure 5 we can see an example of the PFD used during Step 2. The fuel on board is displayed on the left of the compass rose as a weight in kilograms. Just above the Fuel Flow is displayed in kilograms per hour as shown in Figure 5. The wind arrow, normally on the Navigation Display, is here displayed on the PFD as a circle with an arrow and the wind speed value.

Figure 5: PFD Step 2

At the top of the PFD we can see the Flight Mode Annunciator (FMA). The autopilot was in a selected mode and not managed mode. The pilot can select the VHF1 and VHF2 frequencies to communicate with ATC (Air Traffic Control) in a menu that opens on the right of the PFD like in Figure 6.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

Figure 6: VHF

Below the altitude and the standard atmospheric pressure (1013hPa), is the Decision Height (DH) displayed. And below DH, is the radio navigation NAV mode (VOR/ILS) and its frequency selected.

As background is a Synthetic Vision System (SVS) providing the flying environment including terrain, obstacles and other topographical data by replacing conventional sky and ground depiction on the PFD.

In Figure 7 the failure appeared and the name of the failure is displayed on the top right. The pilots can press it to stop the alarm and open the (Electronic Centralised Aircraft Monitor) ECAM procedure.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

Figure 7: AC BUS 1 Fault Step 2

After turning off the alarm a red bell is displayed as reminder of the failure, as shown in Figure 8.

Figure 8: After turned off the failure alarm

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

The pilots can open it again to see the name of the failure at any time or to open the ECAM procedure or Inoperative Systems list (Figure 9).

Figure 9: Touch to open the ECAM procedure

The Navigation Display (ND)

The Time Line

On the ND it's possible to open a time line on the right of the display as shown in Figure 10. Like in a FMC the time line shows the next waypoints, the speed, altitude restrictions of the approach procedure for each waypoint and the time of passage (overflight time).

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

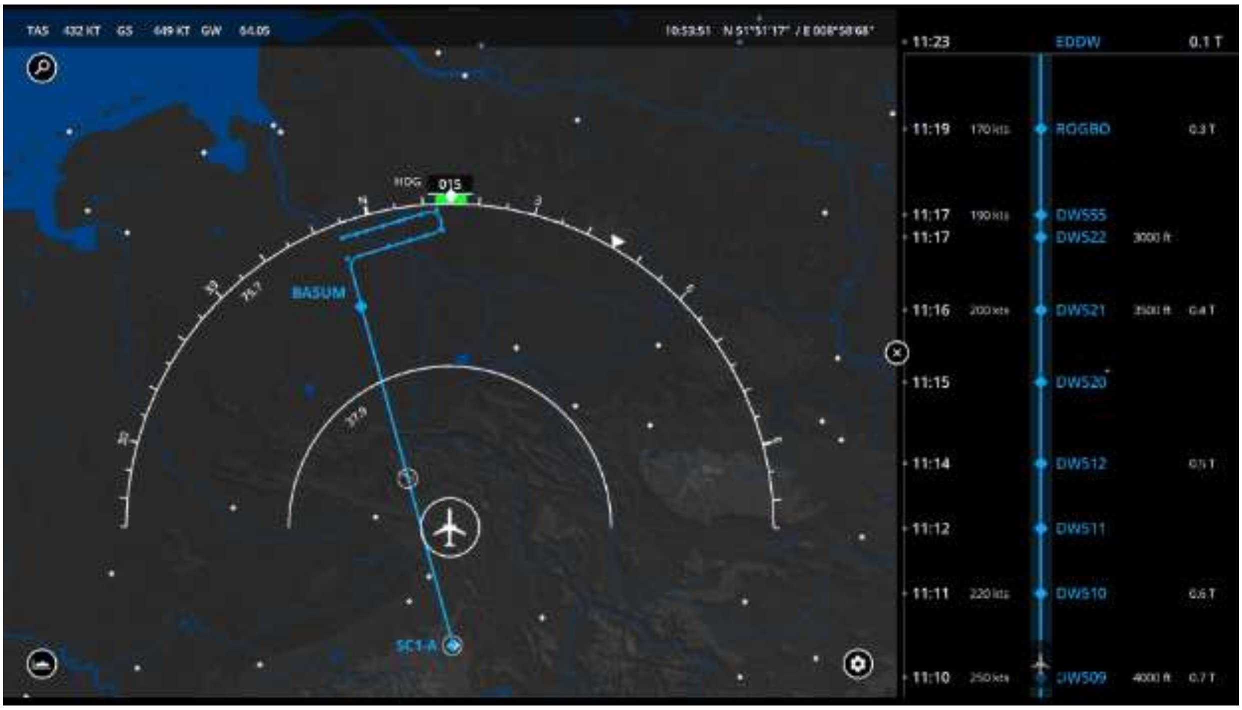


Figure 10: ND Step 2

ND zoom scales

It was possible for the pilots to zoom in and out on the Navigation Display by sliding with the fingers. The scale is therefore free like shown in Figure 11 with a scale of 75.7NM.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

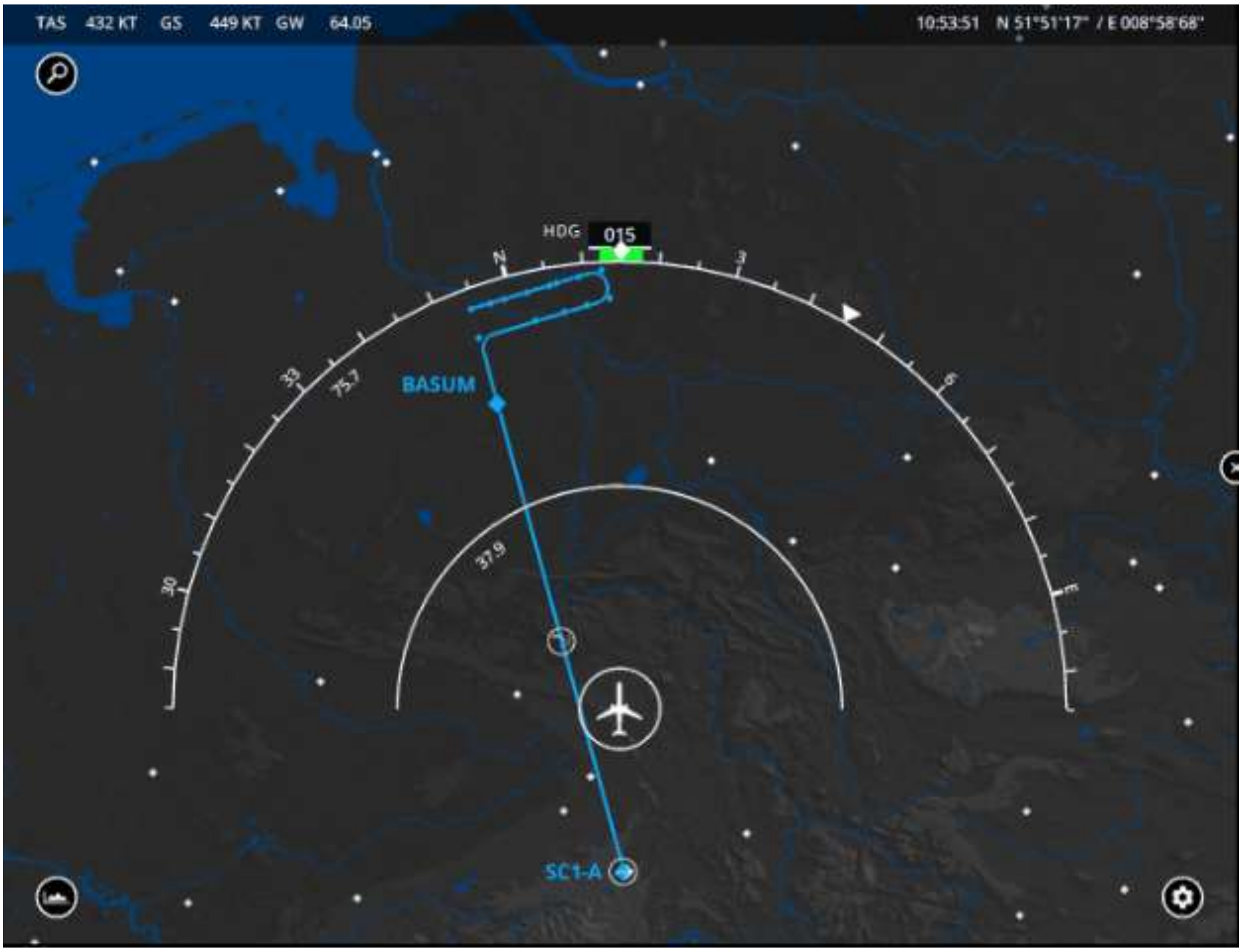


Figure 11: ND Scale 1

In Figure 12 we can see a different scale chosen by the pilots of 46NM. The scales were free and not imposed by the interface like in the legacy A320 where the scales possible are 10NM, 20NM, 40NM, 80NM, 160NM, 320NM.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

Figure 12: ND Scale 2

In Figure 11 and Figure 12 we can see on the top, the information about the Global Weight (GW 64.05 Tons Figure 11 and 63.99 Tons Figure 12) of the aircraft.

The Electronic Centralised Aircraft Monitor (ECAM)

When the AC BUS 1 Fault appears, the pilot opens the ECAM resolution procedure (Figure 13). The pilots press each item one by one. The first item turn the blower to Override, the second item turn the Generator 1 OFF and the third item turn the Generator 1 ON.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

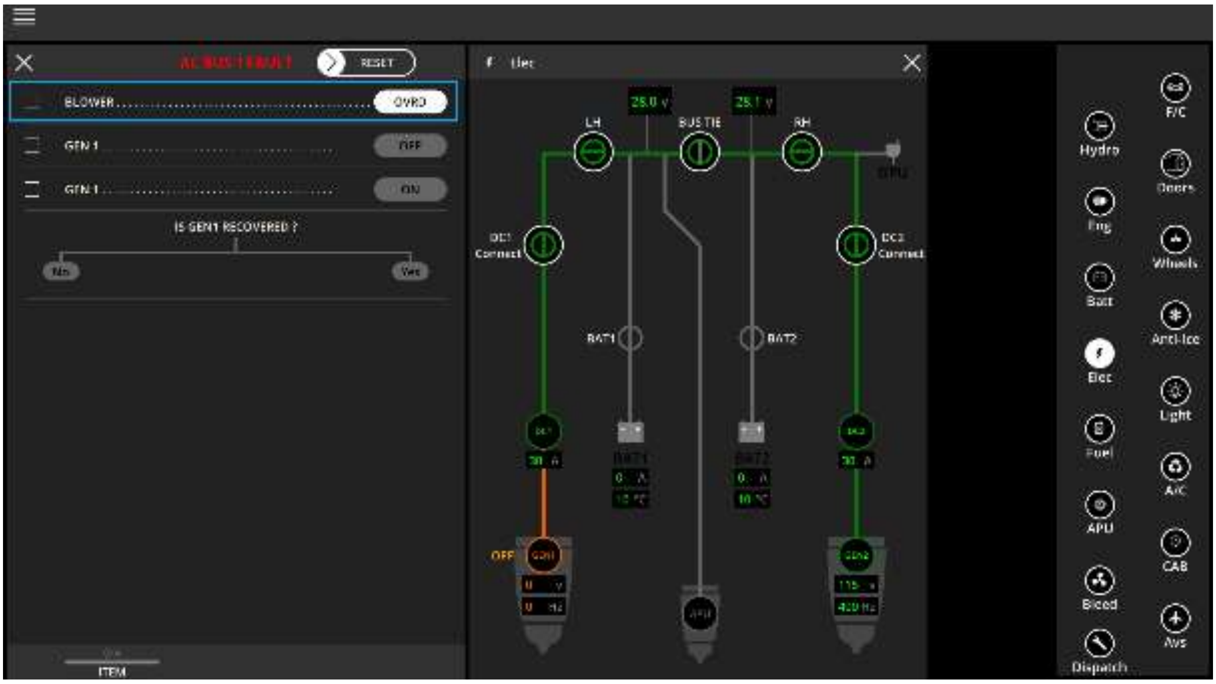


Figure 13: ECAM AC BUS 1 FAULT Part 1

Then the pilot selects "Yes" or "No" if the GEN 1 is recovered and the rest of the procedure opens accordingly (Figure 14). The pilot continues in the same way for the rest of the procedure.

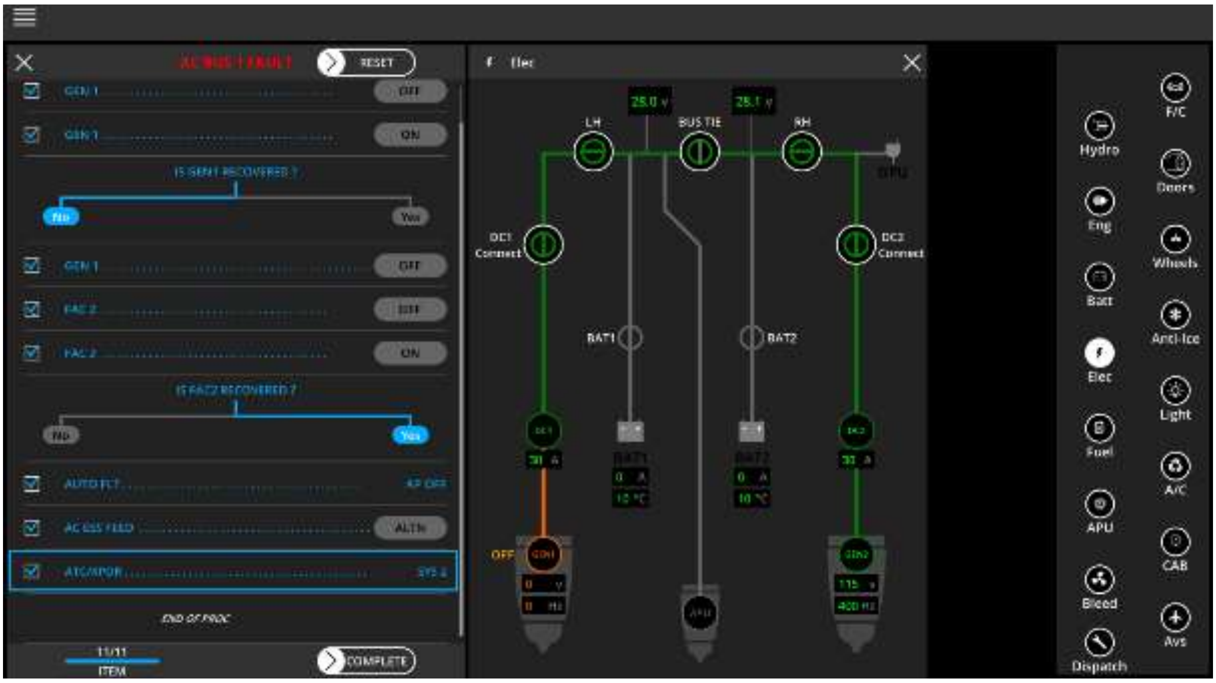


Figure 14: ECAM AC BUS 1 FAULT Part 2

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

At the end of the procedure, the ECAM displays the inoperativ systems as a result of the failure and the resolution procedure, on the right of the display. In Figure 15 we can see the list of the inoperativ systems after the AC BUS 1 failure in a A320. In Step 2 the list is the same as in an A320 but the order changes. The list is sorted by importance for the landing.

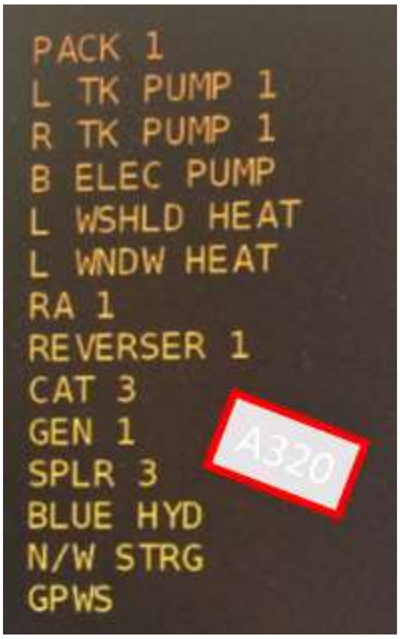


Figure 15: INOP SYSTEMS A320

2.5.2. STEP 3 Interface description

The platform used for Step 3 evaluations is identical to the one of Step 2 (see chapter above). Only software and associated user interface are different in the Step 3.

Primary Flight Display (PFD)

The Primary Flight Display (PFD) in Step 3 has a different gauge to represent the fuel quantity in kilograms and displays the remaining flight time above. The fuel's gauge is on the left of the compass rose as shown in Figure 16. The wind representation relative to the plane is also displayed on the PFD (Figure 16) on the left of the compass rose.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

Figure 16: PFD Step 3

In the Figure 17 we can see that the remaining fuel time is less than the legal 30min and is therefore displayed in red. The failure already happen and a red bell is displayed on the top right. The pilots can press it to stop the alarm and open the (Electronic Centralised Aircraft Monitor) ECAM procedure.

Figure 17: PFD Fuel time left <30min

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

When the pilot press the bell, a banner opens, displays the name of the failure (Figure 18) and opens the failure procedure on the ECAM.

Figure 18: Failure display

Navigation Display

The Navigation Display is the same as on Step 2. Circles were added as fuel representation.

The orange circle

An orange and a red circle are displayed on the Navigation Display (ND). The orange circle shows the flight distance reachable with 30min (1200kgs) of fuel remaining in the tanks (OACI legal fuel reserve).

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

Figure 19: Orange circle at beginning of the scenario

It includes the alternate airports reachable after joining destination airport. The alternates out of the orange circle may still be reachable via a direct route (Figure 19, Figure 20).

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

Figure 20: Orange circle after Go Around

The red circle

The red circle shows the flight distance reachable with the fuel remaining in the tanks before it runs out of fuel and don't take into account the hover time (Figure 21).

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

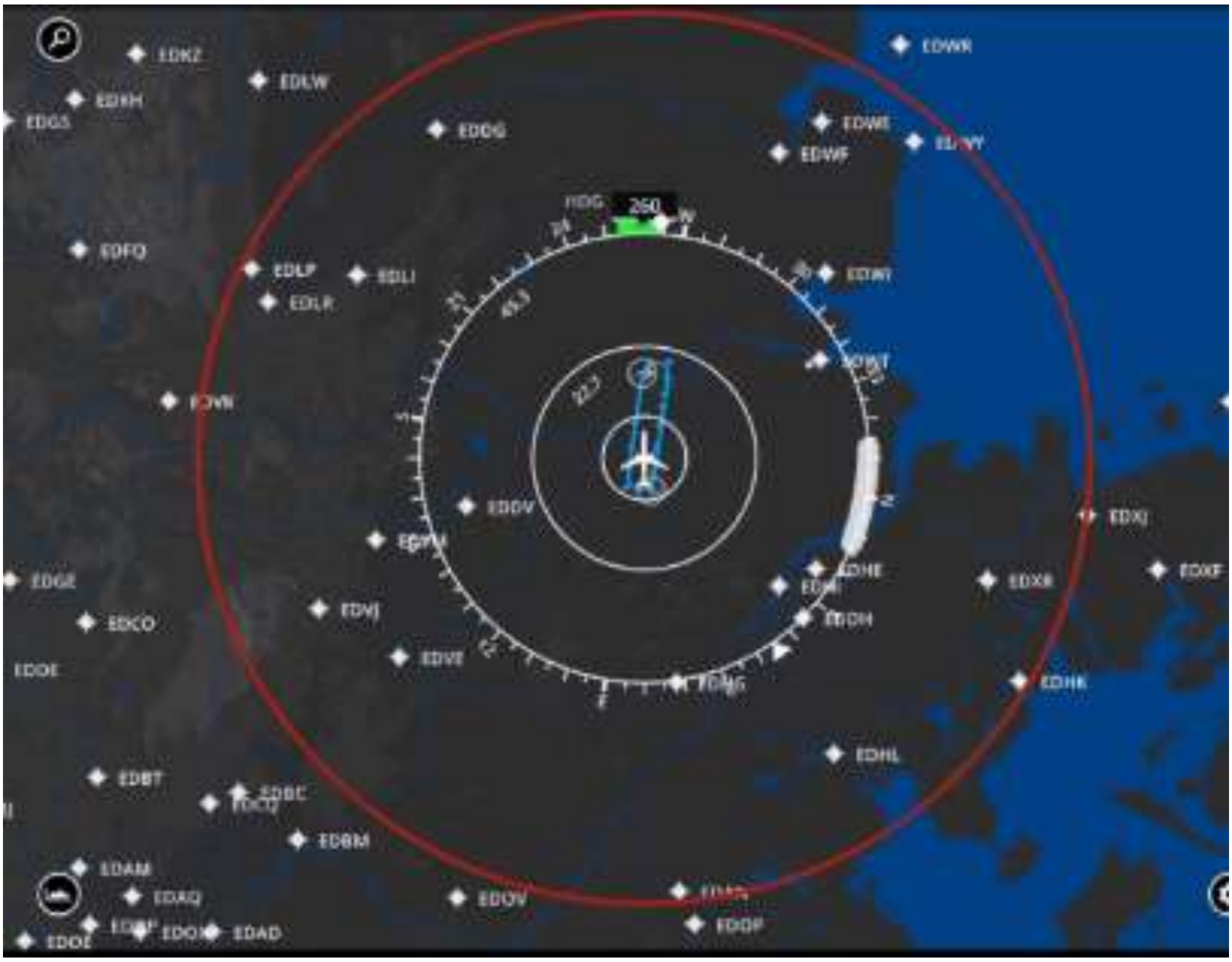


Figure 21: Red circle after the GA

Airports and Runways available

On the ND the pilots can select the airport of their choice and see the runways available. The runways availability is calculated according to the aircraft status and the airport weather. In the Figure 22 we can see that, after the failure and the new weather, the only runway available in Bremen (EDDW) is the RWY09.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

Figure 22: Runway available in EDDW

The time line

As for Step 2 the time line is present in Step 3 (Figure 23).

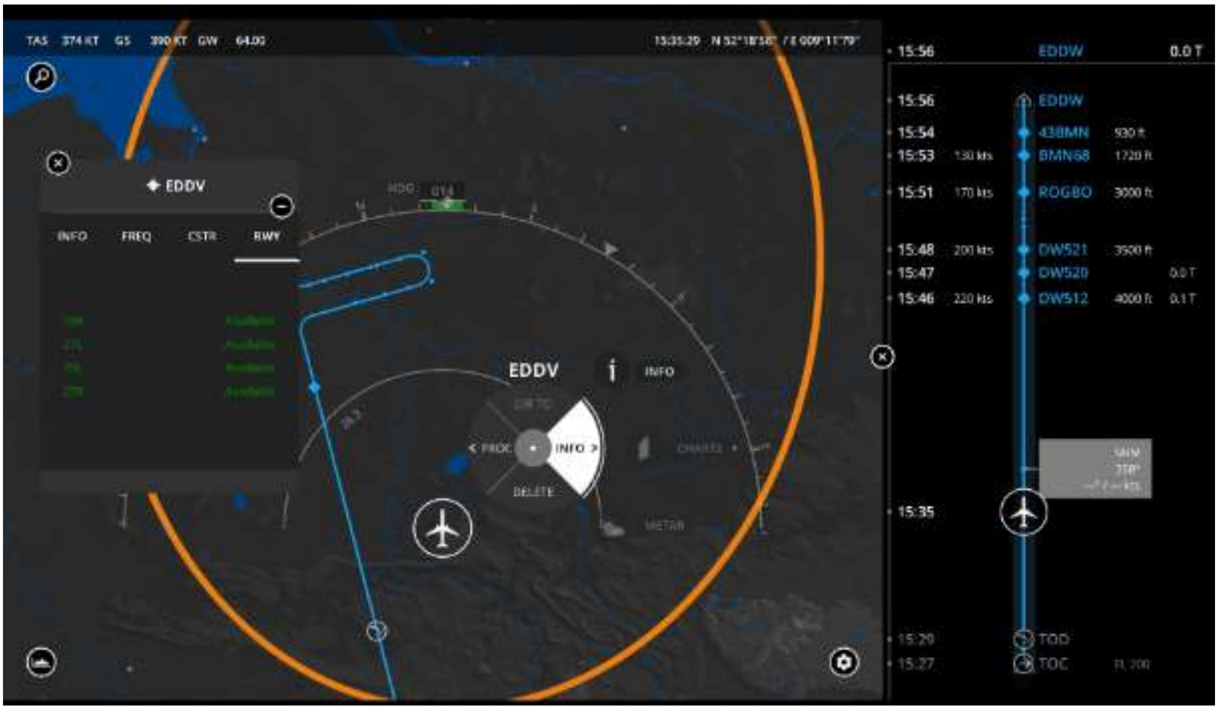


Figure 23: Time line

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

The Electronic Centralised Aircraft Monitor (ECAM)

When the AC BUS 1 Fault appears, the pilots open the ECAM resolution procedure (Figure 24). The pilots press each item one by one. The first item turn the blower to Override, the second item turn the Generator 1 OFF and the third item turn the Generator 1 ON.

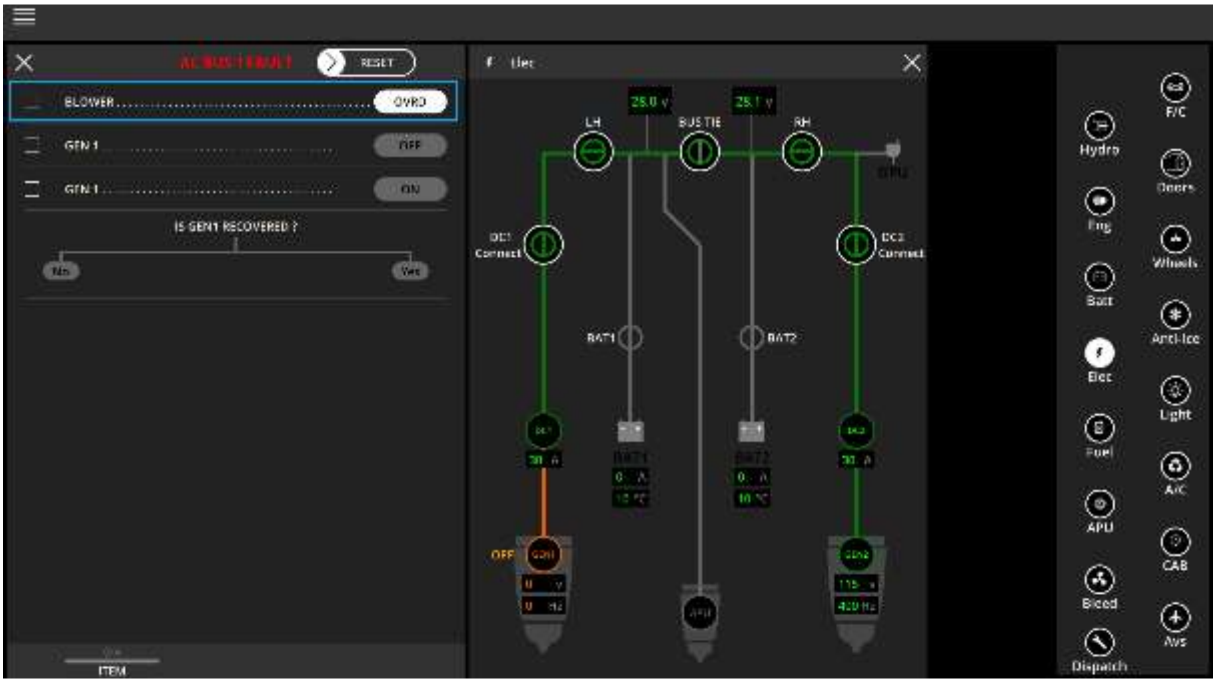


Figure 24: ECAM AC BUS 1 FAULT Part 1

Than the pilots select "Yes" or "No" if the GEN 1 is recovered and the rest of the procedure opens accordingly (Figure 25). The pilots continue in the same way for the rest of the procedure.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

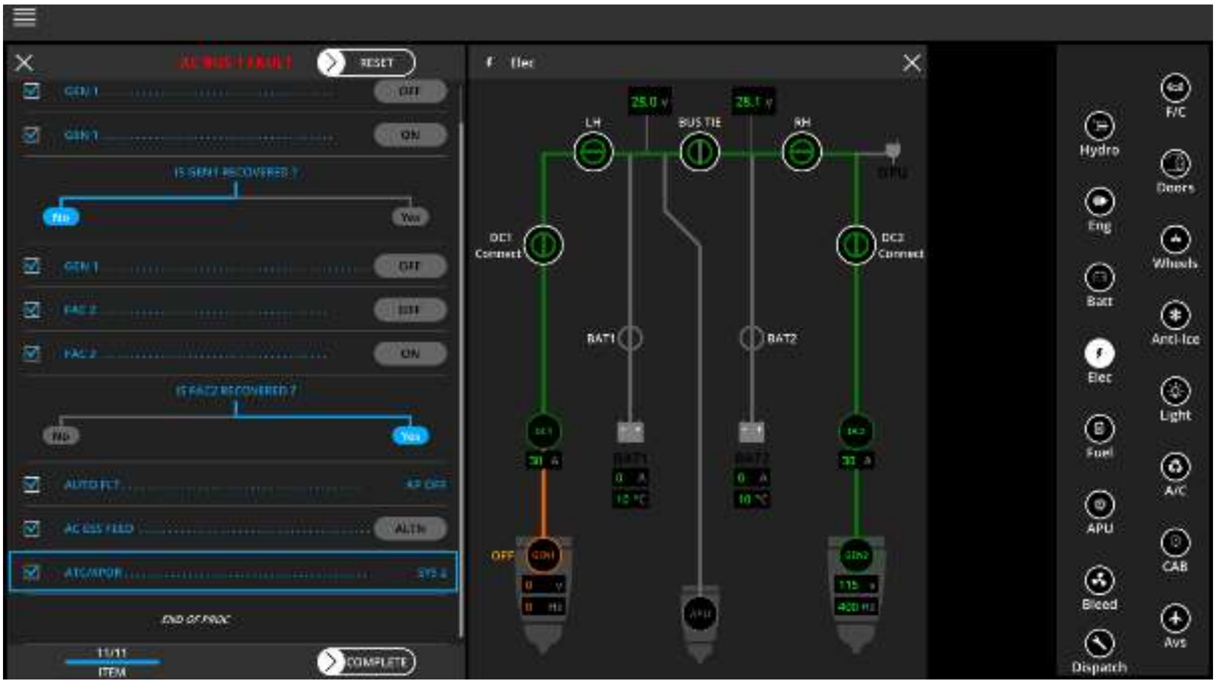


Figure 25: ECAM AC BUS 1 FAULT Part 2

At the end of the procedure, the ECAM displays the inoperativ systems as a result of the failure and the resolution procedure like in Figure 26, on the right of the display. In addition to the list of the inoperativ systems in Step 3, there is a list of their limitations for the landing in front of each item(Figure 26, Figure 27).

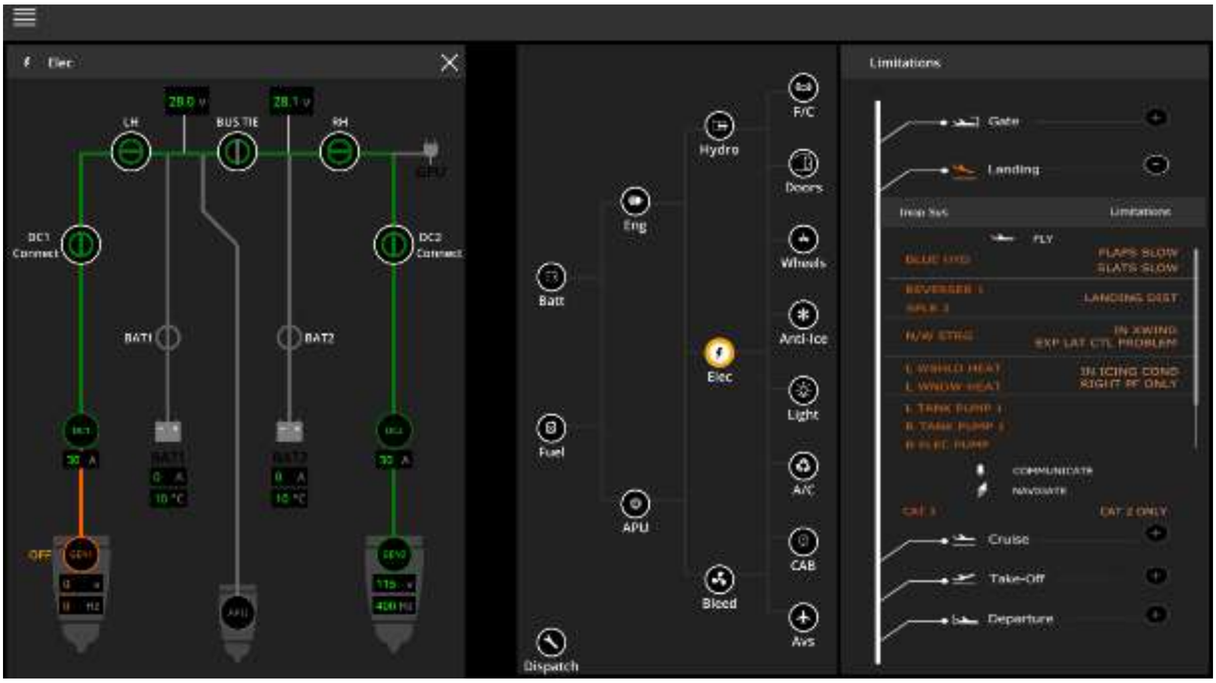


Figure 26: ECAM AC BUS 1 FAULT Part 3 INOP systems

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

Figure 27: INOP systems and their limitations

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

2.6. Summary of procedure

Twenty professional First Officers (FO) from a major airline flying Airbus A320 took part in the second simulator experiments. During the test scenario, they had the role of the Pilot Monitoring (PM). The crew was complemented by a captain from the same airlines having the role of the Pilot Flying (PF). Two pilots were invited per day as shown in Table 2. One pilot started the experiments in the morning and one pilot in the afternoon each day.

Table 2: Experiment Schedule

Experiment Schedule		
09.10.2017	Dry run	
10.10.2017	Dry run	
16.10.2017	Experimental run	2 pilots
17.10.2017	Experimental run	2 pilots
18.10.2017	Experimental run	2 pilots
19.10.2017	Experimental run	2 pilots
20.10.2017	Experimental run	2 pilots
23.10.2017	Experimental run	2 pilots
24.10.2017	Experimental run	2 pilots
25.10.2017	Experimental run	2 pilots
26.10.2017	Experimental run	2 pilots
27.10.2017	Experimental run	2 pilots

Ten pilots flew the scenario with the basic HMI of the AV2020 simulator. This set up is called Step 2. The other ten pilots flew the scenario with the enhanced HMI. This set up is called Step 3. Table 3 shows the numbering of the pilots and the associated set up.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

Table 3: Set Up and Numbering of Pilots

Set Up and Numbering of Pilots			
16.10.2017	Morning	Pilot 21	Step 2
	Afternoon	Pilot 22	
17.10.2017	Morning	Pilot 23	Step 2
	Afternoon	Pilot 24	
18.10.2017	Morning	Pilot 25	Step 2
	Afternoon	Pilot 26	
19.10.2017	Morning	Pilot 27	Step 2
	Afternoon	Pilot 28	
20.10.2017	Morning	Pilot 29	Step 2
	Afternoon	Pilot 30	
23.10.2017	Morning	Pilot 31	Step 3
	Afternoon	Pilot 32	
24.10.2017	Morning	Pilot 33	Step 3
	Afternoon	Pilot 34	
25.10.2017	Morning	Pilot 35	Step 3
	Afternoon	Pilot 36	
26.10.2017	Morning	Pilot 37	Step 3
	Afternoon	Pilot 38	
27.10.2017	Morning	Pilot 39	Step 3
	Afternoon	Pilot 40	

The schedule of each day is shown in Table 4 for the pilot starting in the morning and Table 5 for the pilot starting in the afternoon.

The schedule can be broken down into four phases:

1) **Briefing and preparation:** during this phase, the pilots were informed about the project, its objectives and the experiment schedules. They were also provided with some general information about the scenarios (both training and experimental one) and the measuring tools (physiological belt and questionnaires). The consent form was signed and the post-briefing questionnaires were filled in by the pilots: a) Demographic questionnaire, b) NASA TLX weighting c) SACL (to measure

the stress level at the start), and d) SAMN-Perelli (to measure the fatigue level at the start). Finally, the pilots were asked to put on the physiological belt.

2) **Training:** this phase briefed the pilots on technical and operational aspects. The pilots also performed a training scenario in order to familiarise with the new cockpit and new HMI.
3) **Experimental Run:** the level of fatigue (SAMN-Perelli questionnaire) was measured right before the start of the experimental scenario.
4) **Debriefing and Cognitive walkthrough:** this last phase consists of three parts: a) Post-run questionnaire with SAMN-Perelli (to measure the fatigue level at the end), NASA TLX (to measure the workload level during the scenario), SACL (to measure the stress level during the scenario), and SART (to measure the situation awareness during the scenario), b) Cognitive walkthrough, and c) performance curve and benefits questionnaire/interview.

Table 4: Schedule Pilot Morning

Schedule Pilot Morning		
08:45	Welcome & registration	
09:00	Briefing Declaration of Consent Form	Briefing room
09:20	Demographic questionnaire, NASA-TLX weighting, SACL, Samn-Perelli	Briefing room
09:40	Attraction of smart vest	Rest room / Briefing room
10:00	**Training**	AV2020
	•Captain	
11:30	- *Break* -	
11:40	Calibration of eye-tracking	AV2020
11:45	**Experimental run**	AV2020
	•Captain	
	•ATC	Control room
12:45	Samn-Perelli NASA-TLX, SACL, SART	AV2020
13:00	Cognitive walkthrough	Briefing room
14:00	Performance curve Benefits questionnaire	Briefing room
14:15	End	

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

Table 5: Schedule Pilot Afternoon

Schedule Pilot Afternoon		
12:15	Welcome & registration	
12:30	Briefing Declaration of Consent Form	Briefing room
12:50	Demographic questionnaire NASA-TLX weighting, SACL, Samn-Perelli	Lounge
13:10	Attraction of smart vest	Rest room / Lounge
13:30	**Training**	AV2020
	• Captain	
15:00	*- Break -*	
15:10	Calibration of eye-tracking	AV2020
15:15	**Experimental run**	AV2020
	• Captain	
	• ATC	Control room
16:15	Samn-Perelli NASA-TLX, SACL, SART	AV2020
16:30	Cognitive walkthrough	Briefing room
17:30	Performance curve Benefits questionnaire	Briefing room
17:45	End	

2.7. Pilots

Twenty professional pilots participated in the second simulator experiments. All pilots were first officers flying Airbus A320. Among the participants were two female and eighteen male pilots. Ten pilots flew the scenario under step 2 and ten under step 3 condition. Their age was between 28 and 41 with a mean of 32.4 for step 2 and 33.1 for step 3.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

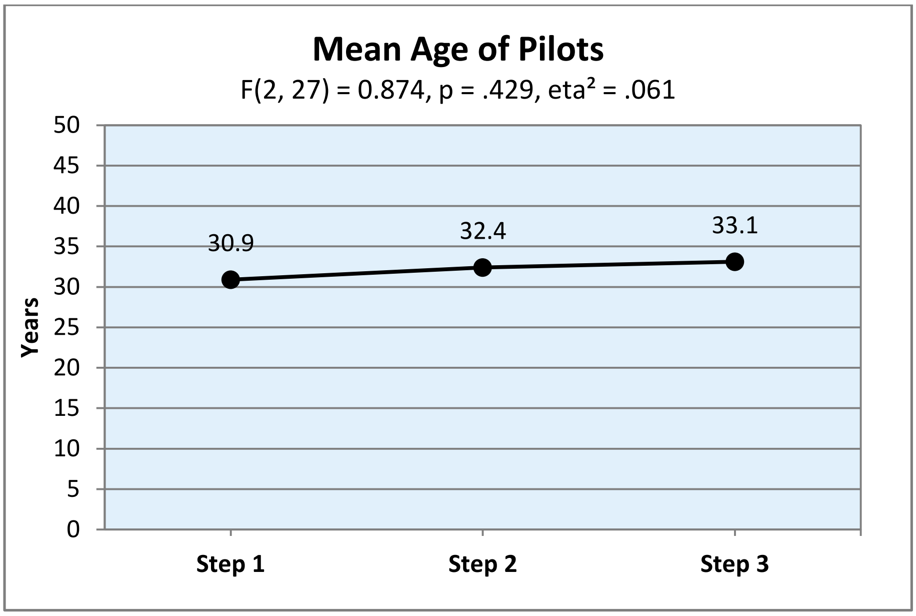


Figure 28: Mean age of pilots participating in the experiments

The mean flight hours on the A320 family was 3735 hours for step 2 and 4435 hours for step 3. Even though the value for step 3 is slightly higher, there is no significant difference between step 2 and step 3.

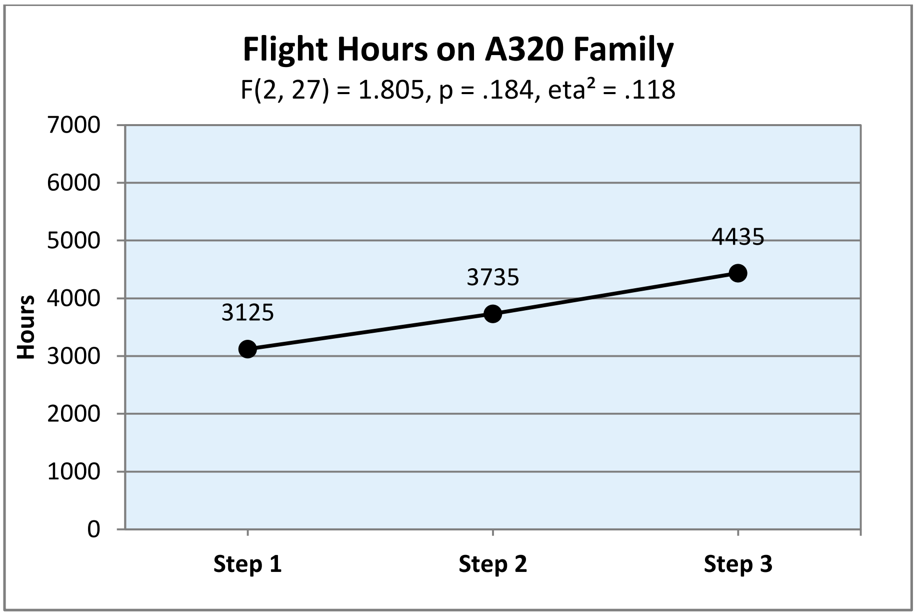


Figure 29: Mean number of flight hours on A320 Family

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

In average, the pilots had flown 563 hours in step 2 and 681 hours in step 3 within the last twelve month. The current experience of all pilots was fully acceptable ranging from 330 hours to 800 hours within the last twelve month.

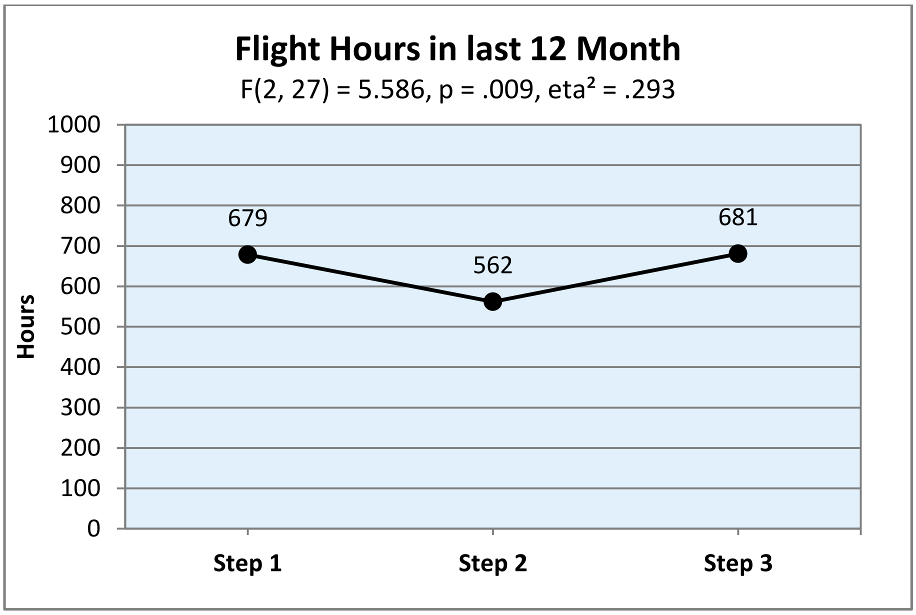


Figure 30: Mean number of flight hours in the last twelve month

The total number of flight hours ranged from 2250 hours to 8500 hours with a mean of 4801 hours in step 2 and 4680 hours in step 3. The numbers highlight that all pilot were experienced pilots.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

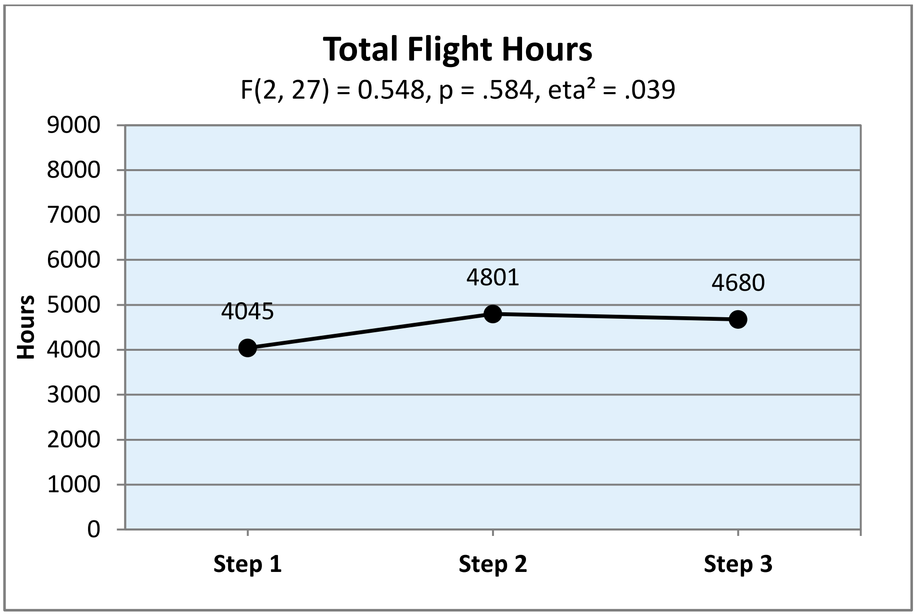


Figure 31: Mean number of total flight hours

2.8. Subjective data

2.8.1. Fatigue

The fatigue of the pilots was measured in order to determine its influence on the performance. The SAMN-Perelli fatigue scale was used as a measurement. It consists of a 7-point scale:

1 = fully alert, wide awake
2 = very lively, responsive, but not at peak
3 = okay, somewhat fresh
4 =a little tired, less than fresh
5= moderately tired, let down
6 =extremely tired, very difficult to concentrate
7= completely exhausted, unable to function effectively

The level of fatigue was measured three times: post briefing, pre experimental run, and post experimental run. Figure 32 shows the level of fatigue at the beginning of the experimental run. The numbers range between 1 “Fully alert, wide awake” and 4 “a little tired, less than fresh”. Figure 33 shows the level of fatigue at the end of the experimental run. Here the numbers also range between 1 and 4. The data for pilot 1 are missing unfortunately.

Future Sky Safety has received funding from the EU’s Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

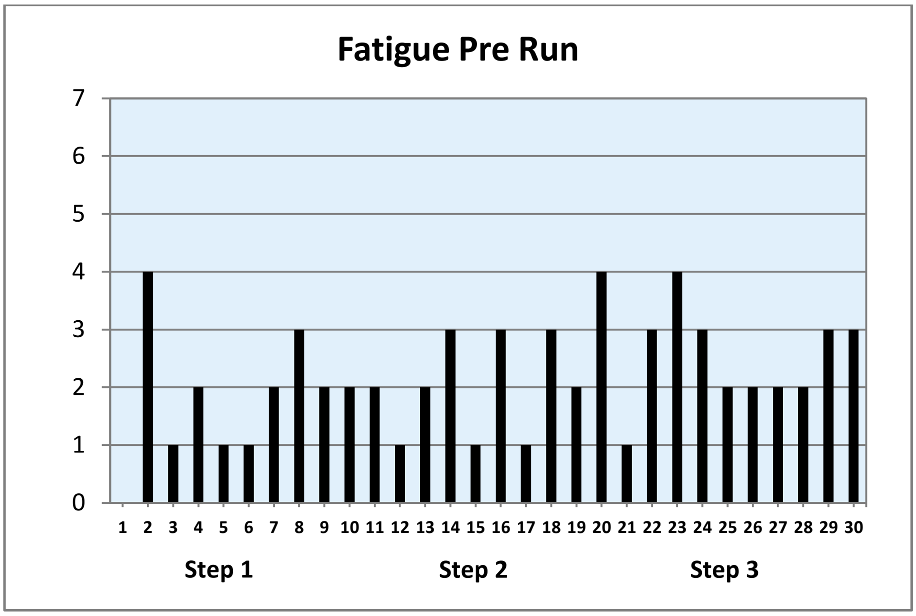


Figure 32: Level of fatigue pre experimental run

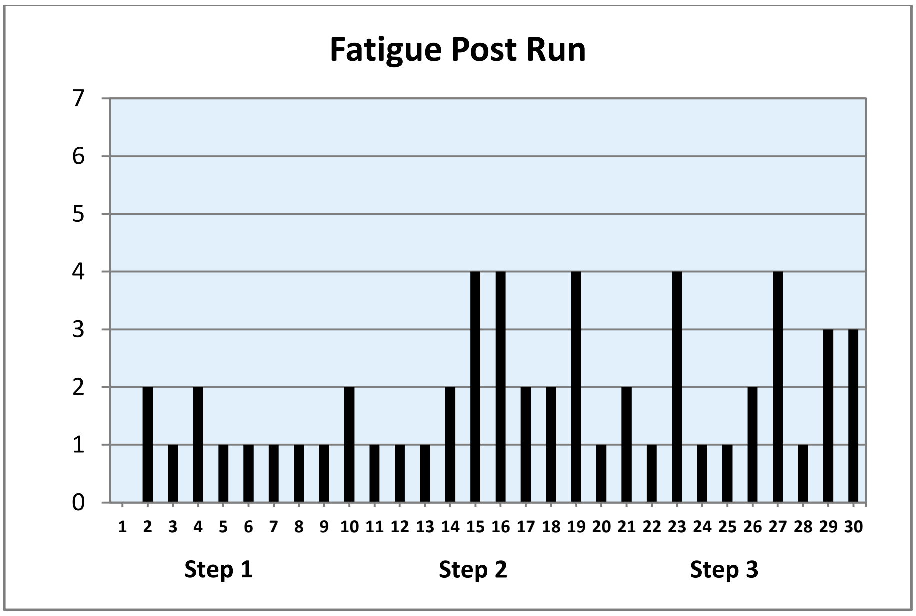


Figure 33: Level of fatigue post experimental run

Figure 34 compares the level of fatigue for each pilot at the beginning and end of the experimental run. The results show that for 9 pilots the level did not change, for 13 pilots it improved during th e run, and for 6 pilots it deteriorated during the run. Overall, there are no significant changes in the levels of fatigue from the beginning to the end of the experimental run.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

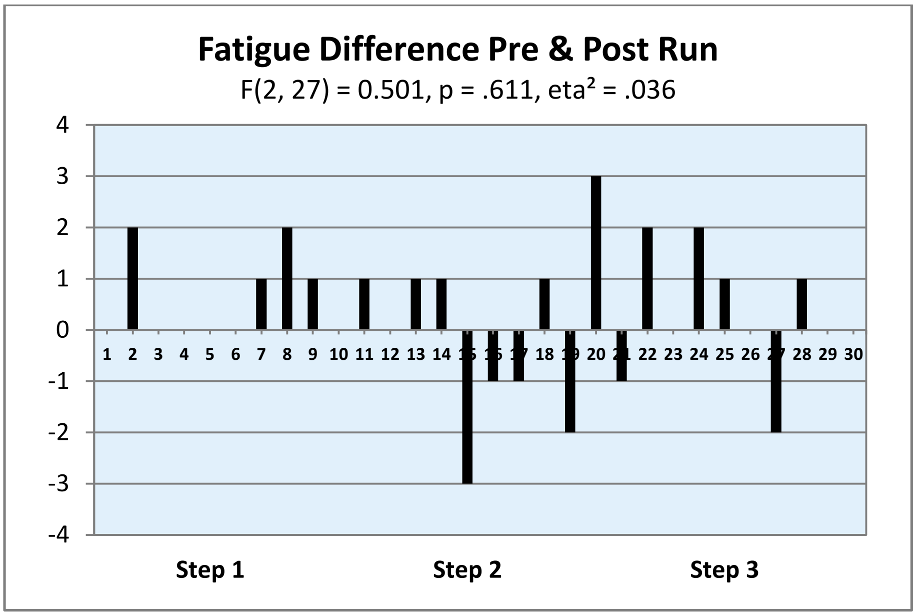


Figure 34: Difference of level of fatigue pre and post experimental run

2.8.2. Workload

The questionnaire used to measure workload was the weighted NASA-TLX. After each run the pilots were required to rate their workload on a scale from 1 to 20 along six factors: mental demand, physical demand, temporal demand, performance, effort, and frustration level. The results show that the overall workload did not significantly change between the different steps as shown in Figure 35. It was almost the same in all steps.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

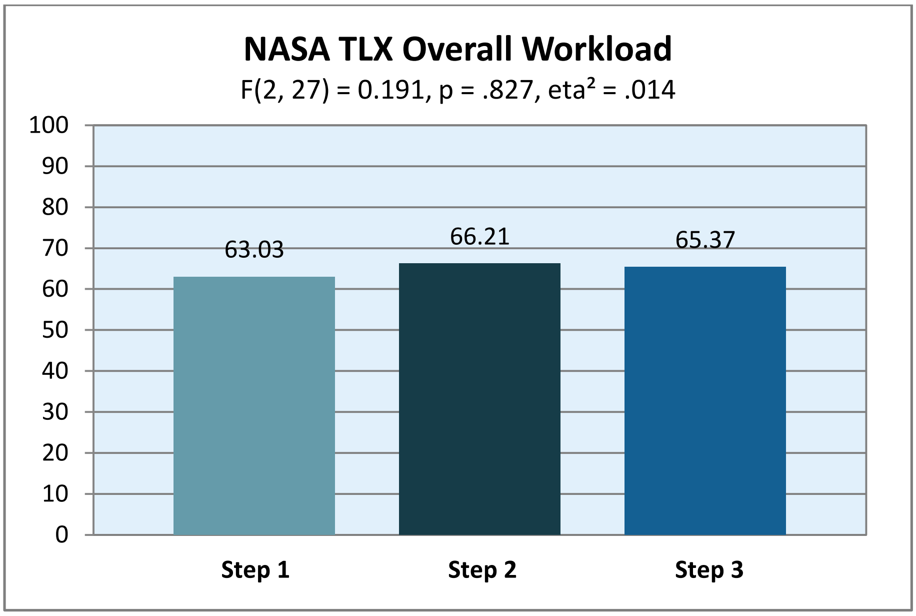


Figure 35: Overall level of workload

Looking at the ratings with regard to mental demand, the results show the highest value at step 1, followed by step 3, and the lowest value for step 2 (see Figure 36). Overall, these differences are not significant.

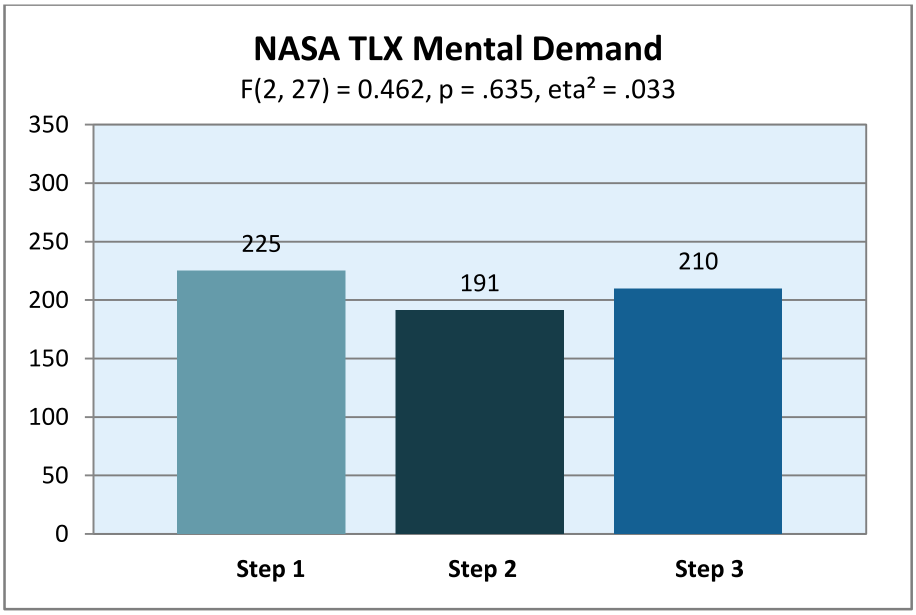


Figure 36: Mental demand

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

The results of the physical demand were also similar between the different steps (no significant difference) and, compared to the other NASA-TLX factors, very low. Figure 37 shows these results.

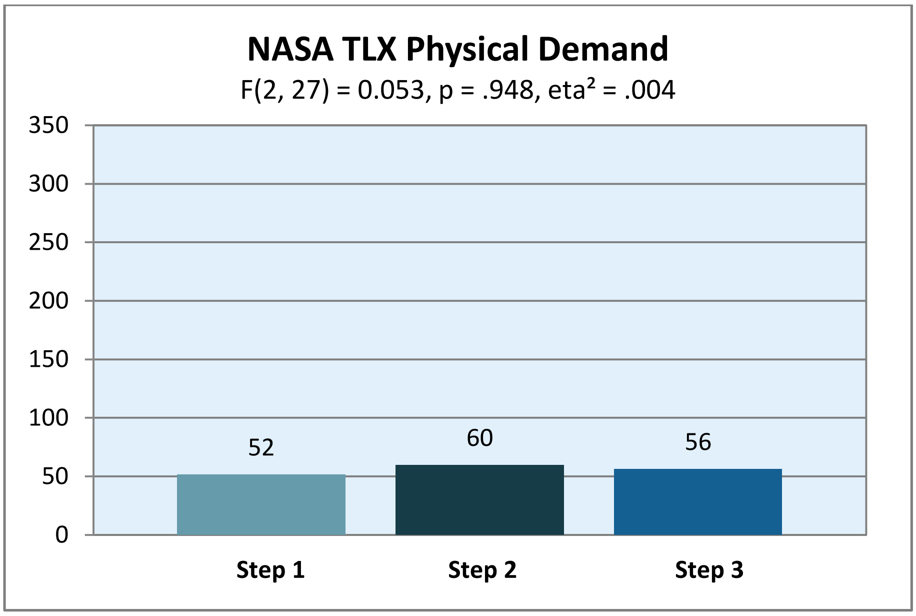


Figure 37: Physical demand

The temporal demand factor of the NASA-TLX was almost the same in step 1 and step 2 but considerably lower in step 3 as shown in Figure 38.

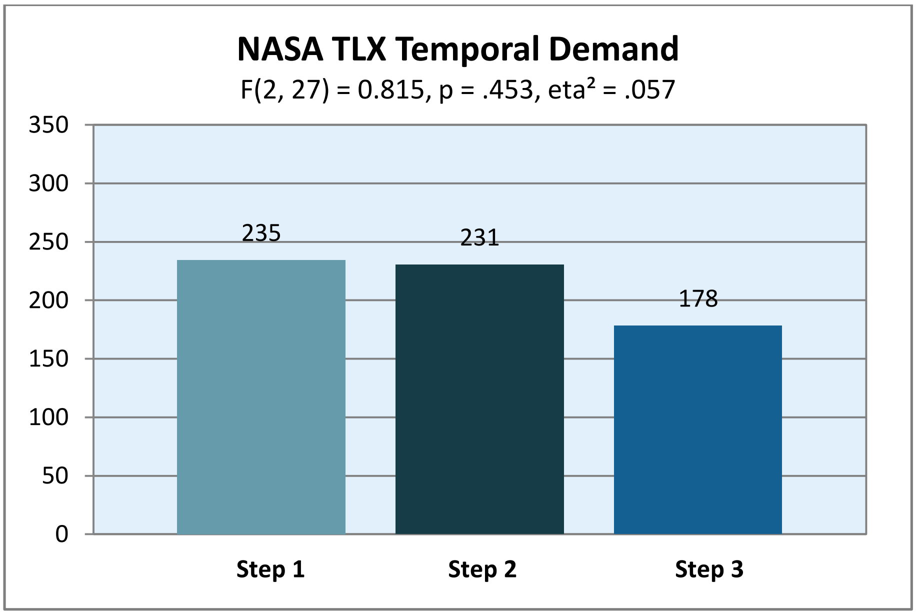


Figure 38: Temporal demand

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

The frustration of the pilots was the highest in step 1 and the lowest in step 3 (see Figure 39), again with a considerably difference.

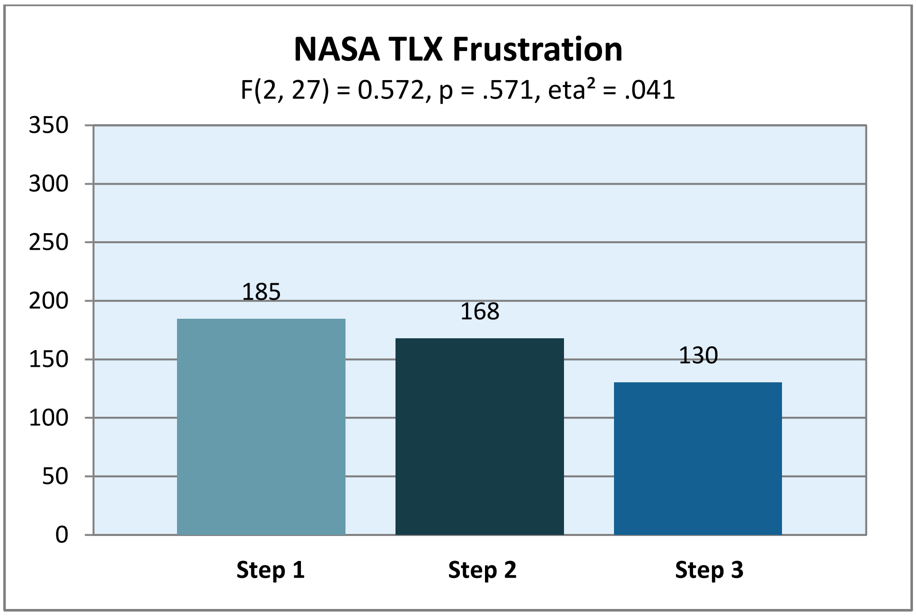


Figure 39: Frustration

The performance of the pilots measured with the NASA-TLX was much higher in step 3 compared to step 1 (seconds highest) and step 2 (lowest). This is shown in Figure 40.

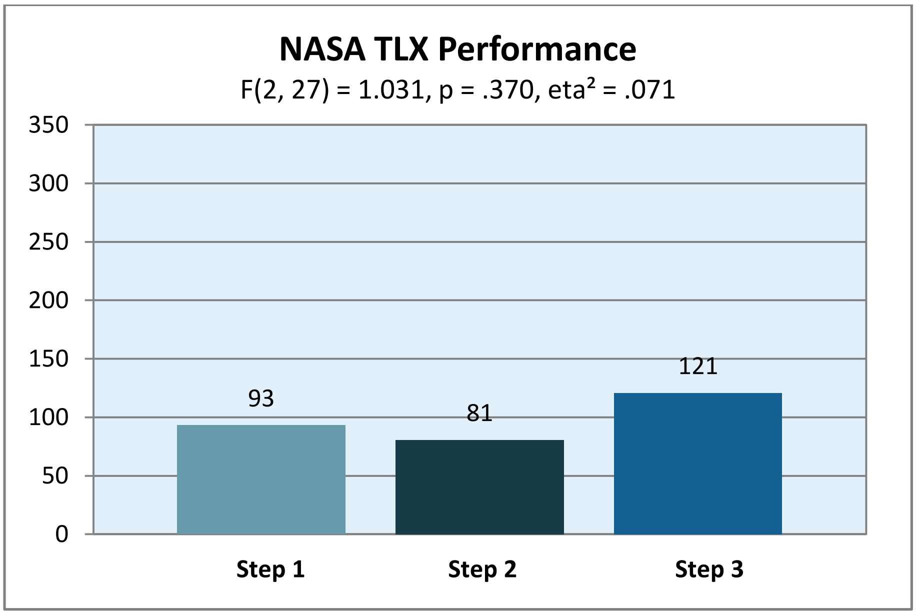


Figure 40: Performance

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

Significant differences existed with regard to the effort pilots had to spend during the run. The value was significantly higher in step 2 compared to step 1 (difference = 106, p = .042) and in step 3 compared to step 1 (difference = 128, p = .012) (see Figure 41).

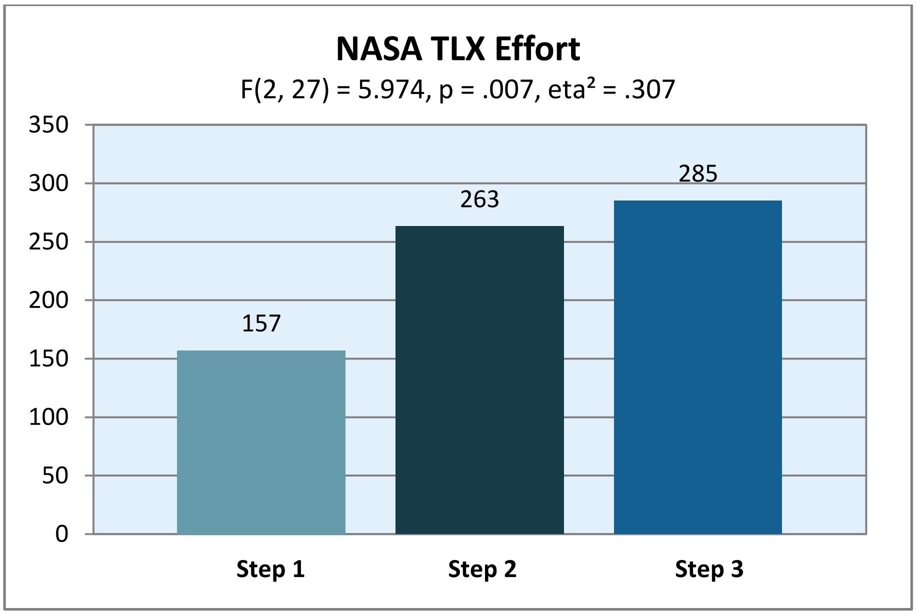


Figure 41: Effort

2.8.3. Stress

Stress was measured with the SACL questionnaire. The SACL distinguishes between two dimensions, arousal and stress. Arousal refers to the attentiveness and wakefulness of a person and stress refers to the unpleasantness and uncomfortableness of a person. The results of the first dimension, arousal, are presented in Figure 42. The values are basically the same for all three steps.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

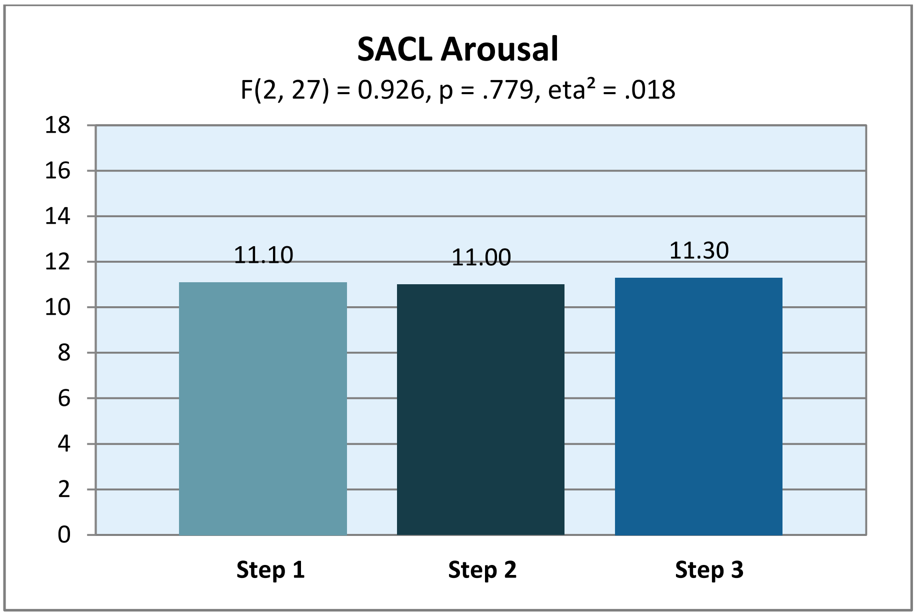


Figure 42: Level of arousal

The results of the second dimension, stress, are presented in Figure 43. The results again show no significant difference and only a slightly lower value in step 2 compared to step 1 and 3.

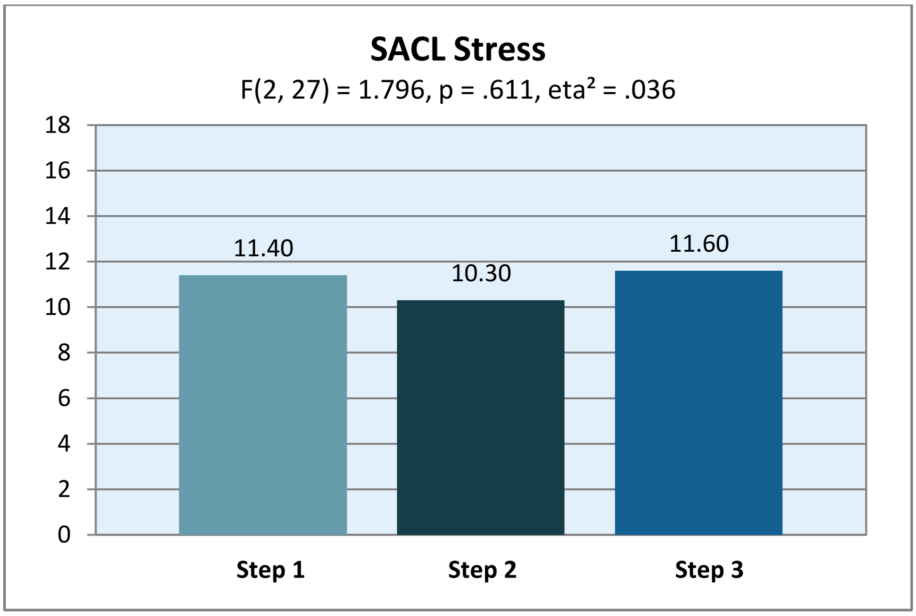


Figure 43: Level of stress

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

2.8.4. Situation awareness

Situation awareness was measured with the SART questionnaire. The SART questionnaire has three dimensions from which a composite SART score for situation awareness is calculated. The first dimension is attentional demand, the second one attentional supply, and the third one understanding. The total score is calculated with the following formula:

Situation awareness = understanding – (attentional demand - attentional supply)

The following four figures will show the results for the three dimensions and the total score for situation awareness. Figure 44 starts with the attentional demand. The demand was slightly higher in step 1 compared to step 2 and 3 but the results were not significantly different.

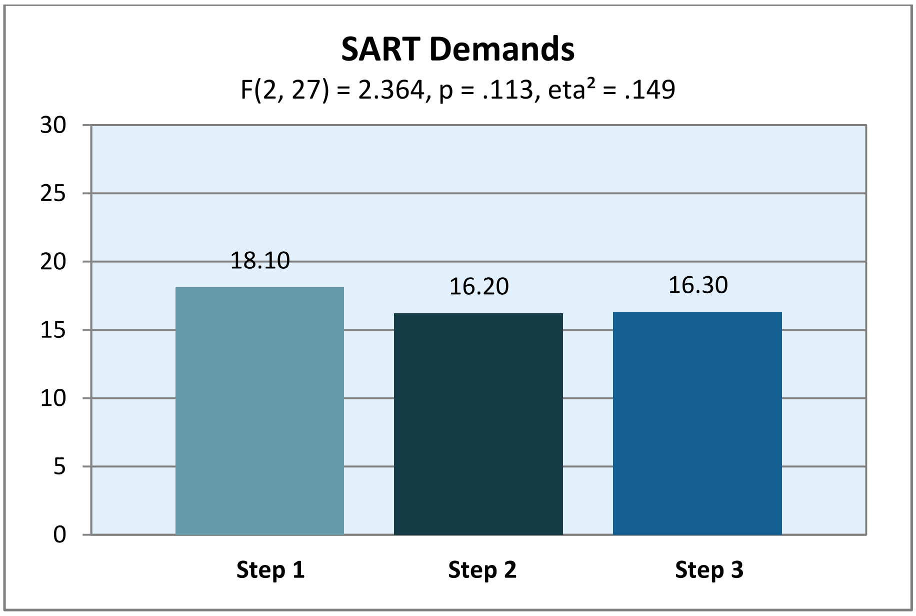


Figure 44: Attentional demand

The next figure, Figure 45, shows the results with respect to the attentional supply. The values were almost the same for the three steps and no significant differences existed.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

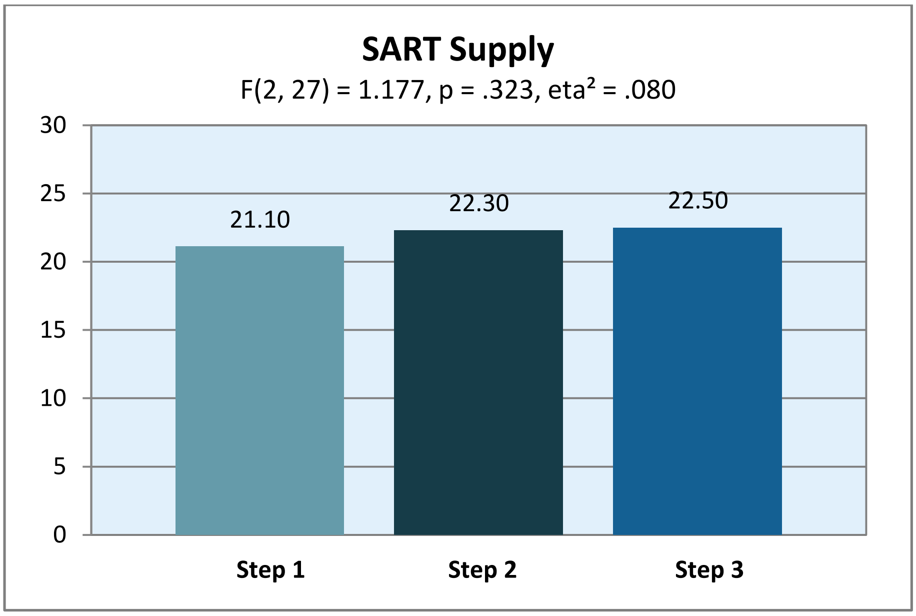


Figure 45: Attentional supply

The results regarding the understanding of the situation by the pilots showed differences (shown in Figure 46). The value was the lowest in step 1 and the highest in step 3. This difference between step 1 and 3 also turned out to be significant (difference = 3.60, p = .003).

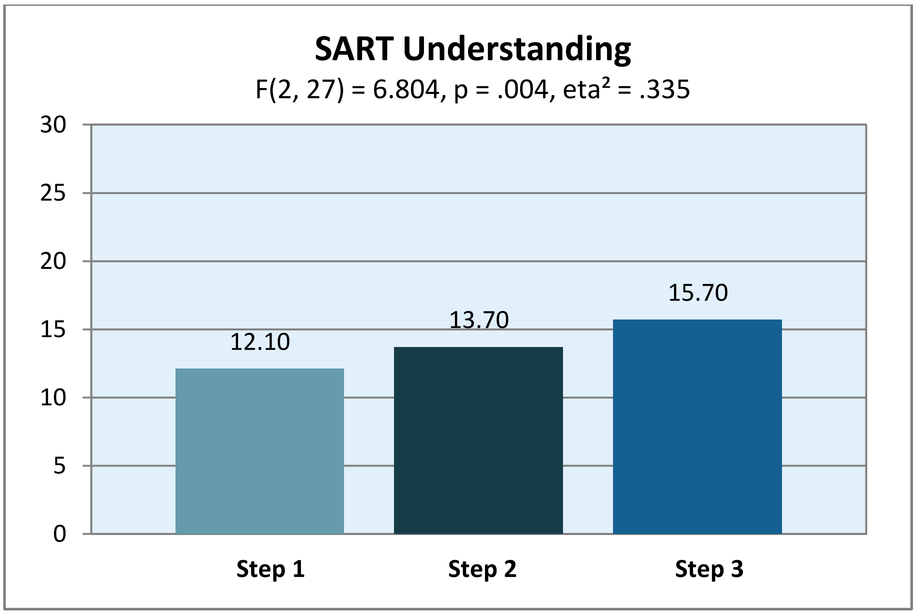


Figure 46: Understanding

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

The overall levels of situation awareness for the three steps are presented in Figure 47. The lowest level of situation awareness was in step 1 followed by step 2. The highest level of situation awareness was in step 3. The difference between step 1 and step 3 was significant (difference = 6.80, p = .004).

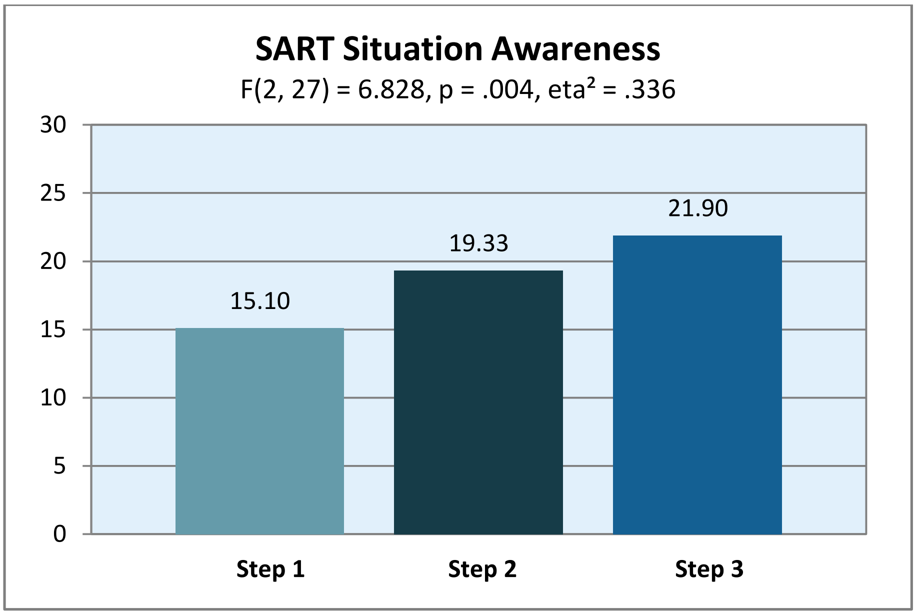


Figure 47: Level of situation awareness

2.8.5. Discussion

The results of the fatigue measurements point out that fatigue had no significant influence on the performance of the pilots. It was intended that this was not the case. Fatigue was not altered in the scenario and only measured in order to determine a possible influence on performance. Therefore, the results confirm that the level of fatigue did not significantly change during the scenario as planned.

The results of the workload and stress measurement highlight that the overall level of workload and stress could not be reduced with the new HMI. This is most probably due to the fact that the pilots had to perform the same tasks in all three steps. The level of automation did not change. This way, no tasks (e.g. flying the aircraft, handling of the failure, planning for the approach) were taken over, for example, by automation, but had to be performed by the pilots. This can explain why the level of workload was the same in all three steps. At the same time, the situation was time critical in all three steps due to the low amount of fuel remaining. Given that the taskload was not reduced and the available time in the scenario not increased, the level of stress was the same in all three steps.

The mental demand on the pilots was the highest in step 1 and the lowest in step 2, but the differences were not significant. This lets conclude that the new HMI do not change the mental demand of the scenario. It remains basically the same. This is probably due to the fact that the complexity of the scenario

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

does not change with the new HMI. This is a fact that was also not intended with the design of the new HMI.

Looking at the results of the temporal demand, the level of frustration, and the performance, the results all show a clear improvement with step 3 compared to step 2 and even more to step 1. The pilots had a lower temporal demand, a lower level of frustration, and a higher performance. I can be concluded that the new HMI reduce the time pressure on the pilots and reduce their feeling of being helplessness and overstrained with the situation in the scenario. The result of this is a better performance of the pilots.

The results of the effort did significantly differ between step 1 and 2 and step 1 and 3. They were much higher in step 2 and 3. This is probably due to the fact that the pilots were confronted with a new cockpit layout with touch screen displays. Even though the main indications and systems were similar to an Airbus A320, some differences surely existed. The time required by the pilots to become totally familiar with the new cockpit and its indications would probably take a few weeks. As it was not possible to provide the pilots this time in the experiments, the effort of the pilots to operate the aircraft with the new cockpit was higher compared to the Airbus A320 cockpit.

The results with the most significant results are those of the situation awareness measurement. The situation awareness was significantly higher with the new HMI in step 3 compared to today's Airbus A320 in step 1. The understanding of the situation in the scenario was significantly higher because the demand on information could be slightly reduced in step 2 and 3 and the supply of information increased. This result confirms the hypothesis that the new HMI improve the pilots' situation awareness as one factor of the global HPE.

2.9. Pupil diameter

2.9.1. Results

The experiment on scenario 1 showed that an increase of workload, an increase of stress, a decrease of situation awareness or a combination of these three factors globally come with an increase of the pupil diameter.

For this second scenario, we want to see if the three conditions significantly change the pupil response during some specific parts of the flight. We want to compare the pupil diameter during the ECAM actions for the three experimental conditions (the three steps), then the pupil diameter during the aircraft status review for the three conditions and finally the pupil diameter during the end of the flight (Frame 2, from the end of the status review to the touch down). We have three hypotheses:

Hypothesis 1 (for ECAM actions)**:** the new avionic (Step 2 and Step 3) should reduce the workload of the crew (compared to the standard A320 cockpit, Step 1) during the ECAM actions. Step 2 and Step 3 should be similar. Also we should have:

Pupil diameter (Step 1) > Pupil diameter (Step 2) ~ Pupil diameter (Step 3)

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

Hypothesis 2 (for status review)**:** the new avionic (Step 2 and Step 3) should improve the situational awareness of the crew (compared to the standard A320 cockpit, Step 1) during the status review process. Step 3, with the advanced representation should improve the SA compared to step 2. Also we should have:

Pupil diameter (Step 1) > Pupil diameter (Step 2) > Pupil diameter (Step 3)

Hypothesis 3 (for frame 2)**:** the new avionic (Step 2 and Step 3) should slightly improve the situational awareness of the crew (compared to the standard A320 cockpit, Step 1). More specifically the crew should be more aware of the fuel situation and the aircraft limitations. This better understanding of how the situation is critical could increase the stress and so we suggest that the pupil diameter should be similar for the 3 steps (SA should decrease the pupil diameter but the stress should have the opposite effect). Also we should have:

Pupil diameter (Step 1) ~ Pupil diameter (Step 2) ~ Pupil diameter (Step 3)

As the pilots for the three steps were not the same ones and the cockpit for step 1 was different from step 2 and 3, we need to normalize the pupil diameter. A one minute baseline was taken just before the bus failure. This baseline is used to calculate the mean pupil diameter and the standard deviation for each pilot and calculate z-values for pupil diameter during the ECAM actions, the review of the aircraft status and the frame 2.

For each pilot, only one eye is kept, the one with the best recording quality. The recording quality is given by the eye tracking tool through a "pupil diameter quality index". Also the analysis process contains the following steps:

1. Filter the pupil diameter data to remove erroneous measure (found thanks to the quality index)
2. Normalize the data (z-values) according to the baseline
3. Calculate the mean and standard deviation and the recording quality for the normalized pupil diameter of each eye during the ECAM actions
4. Calculate the mean and standard deviation and the recording quality for the normalized pupil diameter of each eye during the review of the aircraft status
5. Select for "ECAM actions", "review of aircraft status" and "frame 2" which eye is kept (based on the percentage of erroneous measures identified during the filtering process)

It has to be noted that for frame 2, values of the pupil diameter have been removed when the pilot is looking at its Electronic Flight Bag (and an added 3s recovery period) while the lighting of the EFB is different from the lighting of the other aircraft display. Figure 48 shows the data filtering result with the identification of erroneous data.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

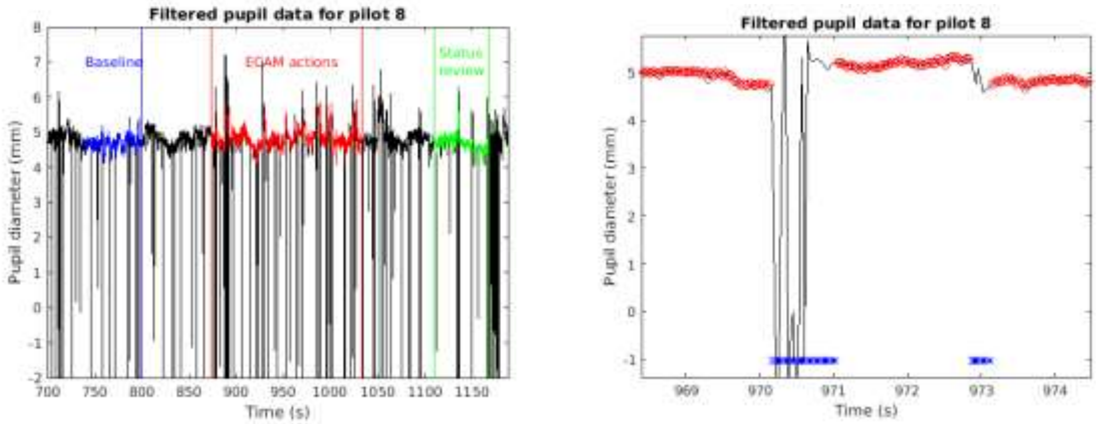


Figure 48: Left part: overview of the raw pupil data (black) and selected data for the baseline (blue), ECAM actions (red) and Status review (green). Right part: detailed view of the result of the filtering process. Red dots are the values kept for the analysis and blue crosses indicate lost values.

The percentage of values removed during the filtering process is calculated for each eye and each target part of the signal. Table 6 indicates these values and the eye selected for each pilot. Percentages of lost values are significantly higher for frame 2 while measures when the pilot is watching the EFB are deleted (and the pilot does watch the EFB for new LAPA calculations).

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

Table 6: Percentage of data lost for each pilot, eye and interest time in the flight. Green cells indicate eye selected for each pilot. Grey cells indicate the three pilots who were not included in the study. Data from pilot 6 are removed only for Frame 2 analysis because the eye tracking recording stopped largely before the touch down.

		Left eye				Right eye			
		baseline	ecam actions	status review	frame 2	baseline	ecam actions	status review	frame 2
Step 1	Pilot 01	No data				No data			
	Pilot 02	19.5	15.5	18.3	65.7	19.7	38.7	52.8	64.6
	Pilot 03	5.4	11.9	5.3	52.2	6.4	11.9	5.8	50.1
	Pilot 04	No data				No data			
	Pilot 05	16.7	17.5	22.5	50.7	13.7	17.6	21.8	50.6
	Pilot 06	13.8	24.6	20.1	49.8	13.3	23.9	16.2	49.2
	Pilot 07	21.4	22.7	32.8	64.5	11.8	13.7	8.5	57.9
	Pilot 08	15.5	17.9	9.1	62.8	7.5	12.9	10.7	62.6
	Pilot 09	15.8	13.0	9.1	56.4	10.9	8.9	7.7	53.1
	Pilot 10	38.9	22.5	16.6	50.3	28.2	18.0	31.7	51.7
Step 2	Pilot 21	66.2	51.6	76.7	72.0	15.8	17.5	9.8	53.4
	Pilot 22	37.9	34.5	49.7	69.1	41.1	37.0	44.5	71.0
	Pilot 23	16.0	11.6	12.3	47.9	23.0	12.0	11.5	48.7
	Pilot 24	17.5	18.7	5.0	48.9	15.7	6.5	2.3	45.2
	Pilot 25	17.5	11.8	13.8	54.0	11.8	19.4	22.0	52.6
	Pilot 26	12.2	12.2	13.6	49.8	11.2	11.6	12.3	50.1
	Pilot 27	59.0	71.3	83.1	79.1	23.6	21.9	50.6	64.4
	Pilot 28	98.9	95.6	99.2	98.2	80.0	65.0	93.9	83.1
	Pilot 29	38.3	29.9	56.6	59.8	11.0	7.4	11.2	49.1
	Pilot 30	6.2	5.7	7.6	47.3	5.1	4.8	11.0	52.5
Step 3	Pilot 31	1.7	6.9	5.5	38.3	1.5	1.0	2.3	38.1
	Pilot 32	100.0	98.7	100.0	99.8	25.8	25.9	31.3	51.4
	Pilot 33	10.5	19.8	31.0	57.6	6.0	10.7	2.4	46.4
	Pilot 34	13.3	13.4	13.1	50.8	24.4	17.6	15.9	51.5
	Pilot 35	5.6	9.0	8.3	45.0	4.1	5.0	3.0	38.9
	Pilot 36	31.1	26.0	41.3	23.7	18.2	10.3	20.0	18.6
	Pilot 37	6.9	16.8	41.8	52.4	9.2	7.6	6.6	48.7
	Pilot 38	9.2	9.8	11.8	55.1	5.1	4.7	6.3	52.1
	Pilot 39	10.9	9.6	38.2	16.9	7.6	4.8	10.6	9.6
	Pilot 40	10.4	7.8	7.8	37.1	12.0	9.2	10.0	38.7

Then, the mean values of the normalized pupil diameter (for the selected eye) are compared by conditions thanks to an ANOVA. Figure 49 shows the results for the ECAM actions values. The pupil diameter for step 1 is significantly different from the two other conditions (see Table 7).

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

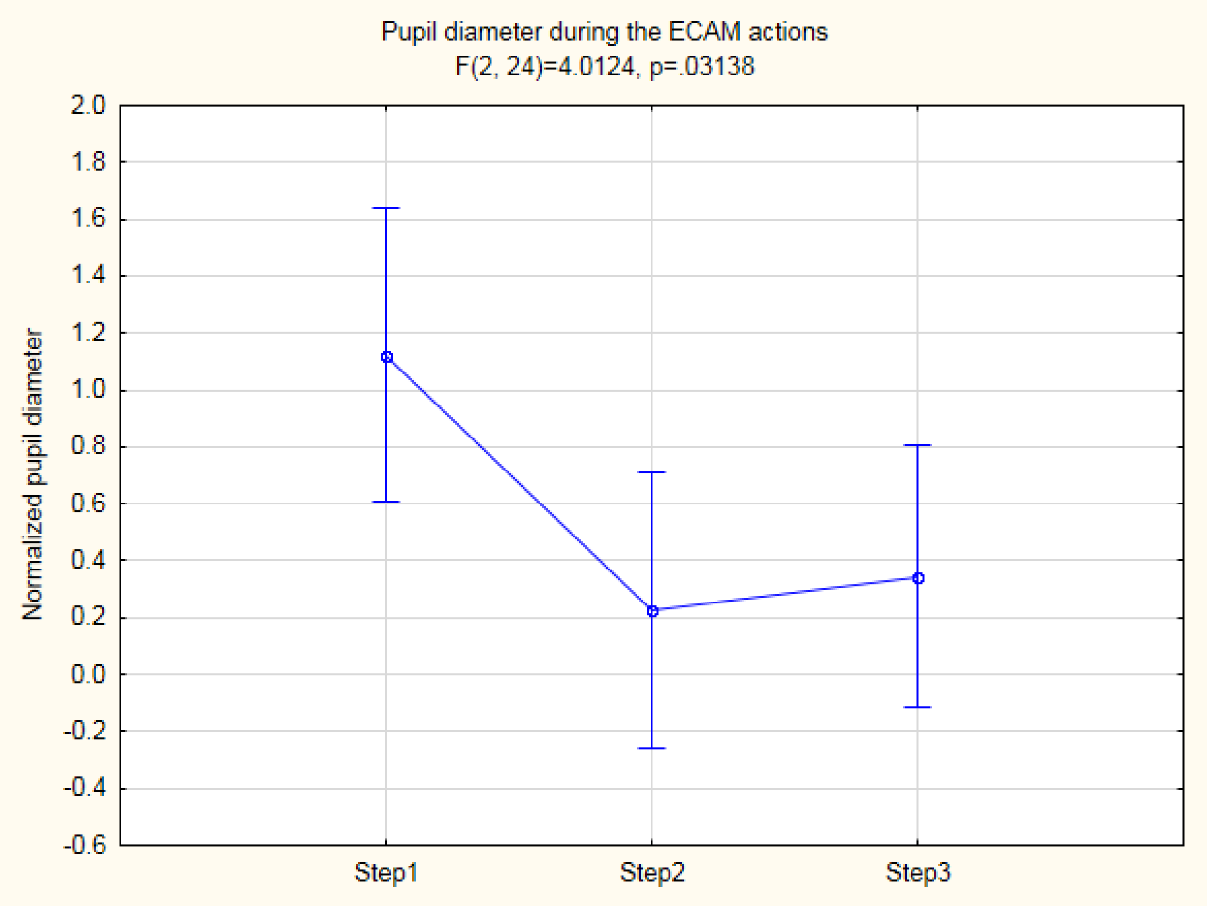


Figure 49: Normalized pupil diameter during the ECAM actions by simulation condition. Blue dots represent the mean normalized pupil diameter by condition; blue line segments represent the confidence intervals at 0.95

Table 7: Newman-Keuls post hoc test (Error MC Inter =.49661, dl=24). The red numbers indicate significant differences

	Step1 1.123141	**Step2** 0.22623	**Step3** 0.34530
Step1		0.033252	0.028561
Step2	0.033252		0.724394
Step3	0.028561	0.724394	

Also this figure indicates that in the A320 cockpit (Step 1) the increase of the pupil diameter during ECAM actions is significantly more important than in the Thales Avionic cockpit (Step 2 and Step 3). We can notice that in the three conditions we have an increase of the pupil diameter compared to the baseline (the mean value for the baseline is 0.00). These results support the Hypothesis 1.

Figure 50 shows the results for the aircraft status review values. There are no significant differences between the three conditions.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

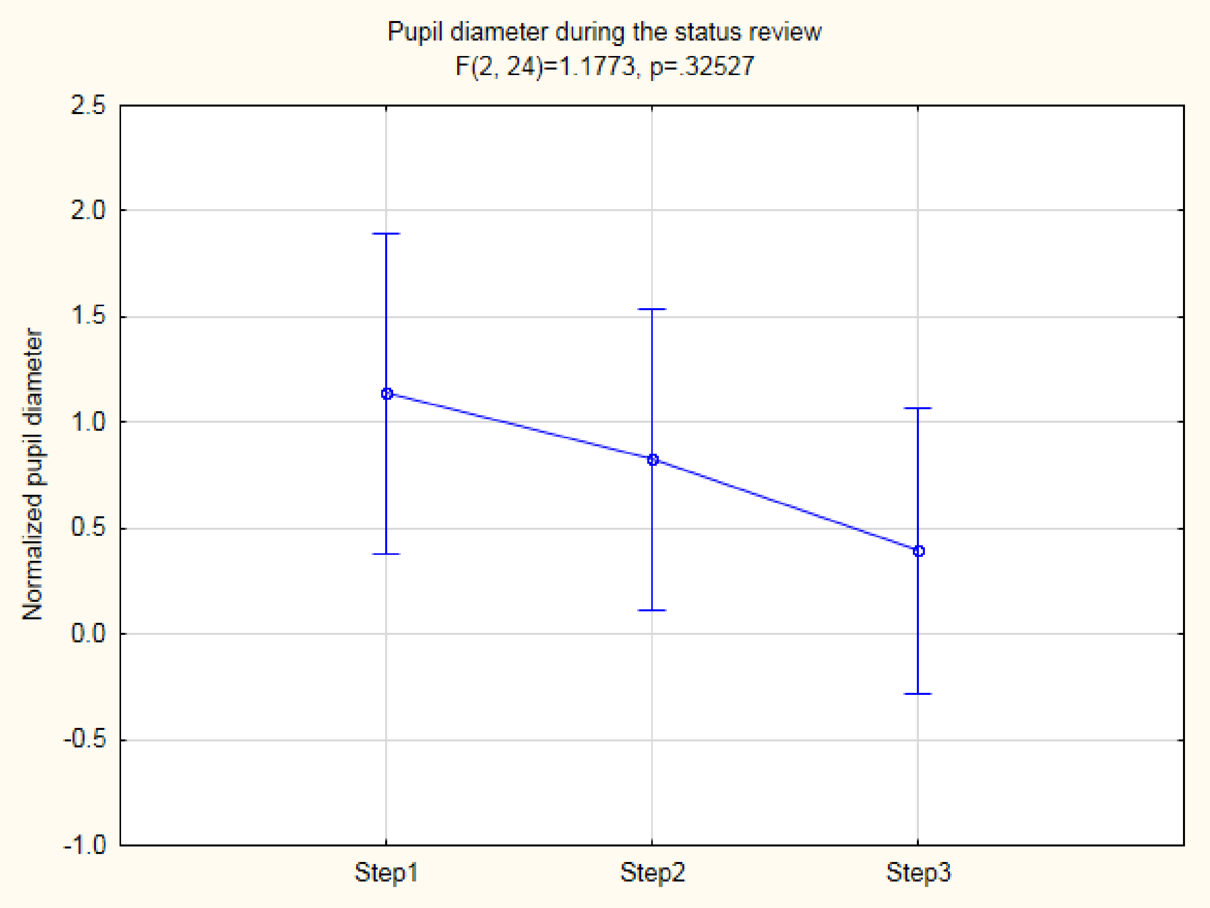


Figure 50: Normalized pupil diameter during the aircraft status review by simulation condition. Blue dots represent the mean normalized pupil diameter by condition; blue line segments represent the confidence intervals at 0.95

Even if we can see a slight decrease of the normalized pupil diameter, these results do not support the second hypothesis. The pupil diameter data does not indicate a real increase of the SA or a decrease of the workload or stress.

Figure 51 shows the results for the frame 2 values. There are no significant differences between the three conditions. This result supports the third hypothesis.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

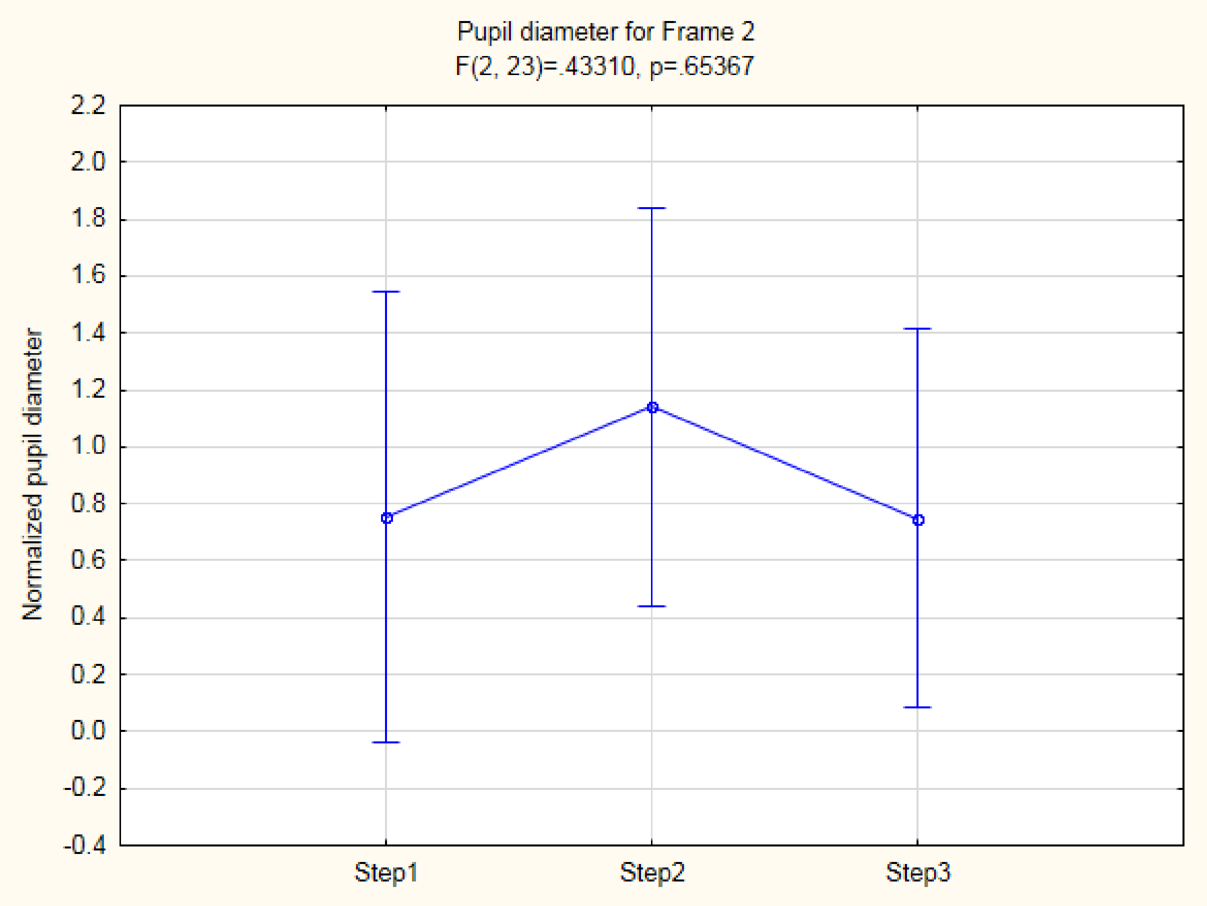


Figure 51: Normalized pupil diameter during frame 2 by simulation condition. Blue dots represent the mean normalized pupil diameter by condition; blue line segments represent the confidence intervals at 0.95

2.9.2. Discussion

While the subjective data (NASA TLX, SACL and SART) describe the overall level of workload, stress or situation awareness, the pupil diameter is used here to consider their respective level for circumscribed tasks.

The results for the ECAM actions task highlight that with the new HMI the pupil normalized diameter is significantly smaller. This lets conclude that the new interface reduce the pilot workload (and perhaps the stress level). All the required information for the ECAM actions is now on the same panel (the pilot is no longer required to look at and move switches on the overall panel) and so the data acquisition is simplified. This is coherent with a smaller pupil diameter. Without surprise, no difference is found between step 2 and step 3.

The review of the aircraft status does not show differences between the three conditions. The impact of the new HMI cannot be observed thanks to the pupil diameter. The amount of information and their complexity are certainly comparable between the three steps.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

Finally, for the end of the flight (from the end of the ECAM procedure to touch down) the normalized pupil diameter are not significantly different for the three conditions. This part of the flight is the one with the higher level of workload and stress in the scenario. Also the result on the pupil diameter could indicate that the HMI does not significantly modify the higher level of workload and stress generated by the scenario.

2.10. Eye-tracking

2.10.1. Introduction

This report details the treatment of the eye tracking data that was captured from twenty pilots during a two-week simulation carried out at Thales in November 2017. The aim of the simulation was to follow on from the previous DLR simulation which used an A320 simulator, and to start to understand the behaviours associated with the use of the Thales AV2020 cockpit concept (referred to as AV2020 in this report). The two systems used in this trial were a standard AV2020, and the AV2020 with added alerts and display improvements. By using the eye tracking data, we can start to understand pilot situation awareness (SA) in response to certain events, and how pilot behaviours were supported (or not) by the technology.

Situation Awareness

The eye tracking data for all pilots indicated that they were focussing on the aircraft controls in order to perceive information as indicated by a dwell time of more than 200ms (Yu et al.,2016). However, differences between the pilots were found and these differences may elucidate how information was used to guide decision making when using the new system. This report makes use of the eye tracking data together with cockpit and eye tracking videos, and subject-matter expert (SME) commentary to begin to understand the pilot behaviours providing a proof of concept for future eye tracking analysis used to understand pilot SA.

Use of eye tracking for HCI analysis

A central tenet of user-centred design is to understand the user and how they interact with a technology. Eye tracking is one method by which the visual behaviour of a user can be understood in greater detail than by observation or interview alone (Jacob & Karn, 2003). Using eye tracking technology, the spatial and temporal characteristics of user visual-behaviour are made accessible to analysis and visualisation (Stephane, 2012). These outputs can then be used by a designer to design or modify the tools and systems that a pilot must interact with, assuming such systems rely on visual inputs.

Eye tracking methods and their output give a system designer another window through which to understand user response to a system in the visual modality. Useful inferences can be made as to where a

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

user is looking, how often they are looking and the overall spatio-temporal scan pattern across multiple displays and controls. It is unlikely that there is a set of firm rules or heuristics with which to derive specific interface solutions. However, together with observation and use of multiple methods inference from eye tracking data can assist the designer in identifying areas for development and modification of displays which support an array of different tasks. Three metrics: scan pattern, fixation duration and number of fixations, are described. These metricscan allow inferences about user behaviour to be made which can assist the system design team.

Scan pattern

An important element of understanding how a user interacts with visual information delivered by the system is the scan pattern (Ellis, 2009). A scan pattern is the spatial distribution of the acquisition of visual inputs (Glenstrup & Engell-Nielsen, 1995). A user may deploy a specific scan pattern depending on a task. Typically, scan in aircraft cockpits is trained at the private pilot license (PPL) level. At the PPL level the classic 'T' of instruments is introduced and a structured scan is trained to develop pilot situation awareness of the aircraft status (Wickens et al, 2001). Separate instruments configured as this classic 'T' have transitioned into a single major instrument, the primary flight display (PFD). In modern glass cockpits the basic scan is still deamnded albeit within a smaller area. In addition to the PFD, modern aircraft contain a number of other displays distributed throughout the cockpit. For example, the central panel, overhead, PFD navigation display (ND) and the engine and system monitoring displays. Understanding how visual information is acquired between these systems for a given task can lead to insights as to where information is best located in the cockpit. For example, if a task demands visual information acquired from dispersed sources necessitating a convoluted scan pattern, this information could be grouped more effectively for that task. A more effective grouping may shorted the scan path and allow for a more efficient synthesis of the information in a single space. Clearly, this will be dependent on the task. However, with appropriate contextual information visual displays can be modified without recourse to changing the physical layout of the cockpit.

Fixation duration

Analysis and visualisation of fixation duration can allow the designer insight into where the more frequently referred to visual information is located (Callan, 2016). As with scan pattern, the most frequently looked at information may indicate the most important or salient information for a given task (Duchowski, 2007). The system designer can then change the grouping of this information, fuse or otherwise combine this information so that it may be more easily understood or acted upon.

Fixation duration can also give the designer an indication as to the difficulty of a visual task when designing or modifying a system. Fixation durations higher than the overall mean duration may indicate that a user is having to work harder to extract meaning from visual information than might be necessary with a different style of display. Design interventions which fuse the information more effectively or

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

change the way in which the information is displayed may reduce fixation duration and improve performance. During interface analysis, fixation data allows the analysit to begin to understand the level of information that the user is processing.

Number of fixations

A high number of individual fixations of shorter duration may indicate inefficient visual search (Salvucci & Goldberg, 2000). If this effect is observed, a designer may wish to change the grouping or salience of information to improve the ability of the user to acquire and search for relevant information in the visual modality (Nakayama & Shimizu, 2004). This may include searching through menu hierarchies or searching for information in electronic flight kits.

This judgment must be made with reference to the task. Conversely, a higher number of longer fixations on a visual display may indicate the relative importance of that display (Jacob & Karn, 2003). The designer may wish to group displays differently or combine information which demands more frequent fixations

2.10.2. Taks Overview

The scenario consisted of the pilots flying a complex scenario, with multiple failures. The sequence of main events is detailed below:

- Starting in cruise followed by approach into Bremen
- Preparation of CAT1 ILS approach RWY 27
- Remaining fuel for about 50 min
- Go-around during ILS approach due to traffic on RWY
- Slight wind shift
- During turn into downwind ELEC AC BUS 1 FAULT
- ECAM procedure
- Decision where to land
- LAPA calculation
- Low fuel situation
- CAT2 ILS approach RWY 09
- Landing

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

2.10.3. Task Breakdown

For the purposes of the eye tracking analysis, the scenario will be split into 3 distinct sections:

Timeframe 1a

- Events from the AC bus failure, to the completion of the ECAM actions

Timeframe 1b

- Limitations from start to finish

Timeframe 2:

- All events from the completion of the limitations to touch down

2.10.4. Method

Participants

Nineteen male and one female participant took part in the Thales simulation. All of the participants are current A320 First Officers. The demographic data can be seen in Table 8.

Table 8: Demographic data

Step	Gender		Age Mean(SD)	Flying hours Mean(SD)	
	Male	Female		A320	Total
2	9	1	32.4(4.8)	3735(1775.1)	4801(2081)
3	9	1	33.1(3.1)	4435(1251)	4680(1492.8)

Eye tracking technology

SensoMotoric Instruments (SMI) eye tracking hardware was used. SMI's eye tracking technology provides binocular tracking up to a 120 Hz sampling rate. Combined with a high definition scene camera and automatic parallax compensation this ensures accurate data over all distances. The SMI BeGaze analysis software supports aggregation of eye tracking data over multiple participants and allows qualitative visualization as well as quantitative analysis of eye tracking data. Data and visuals such as heat maps or key eye tracking metrics can be exported for further analysis as needed.

Approach to analysis

The DLR Software 'Eye Tracking Analyser' was used for eye-tracking data processing. This tool allows for the analysis for areas of interest (AOI) defined within the simulation environment and for event-related eye data analysis such as pupil diameter or fixation duration. First, quality metrics for the eye data were calculated. Data that did not meet quality criteria was excluded from the analysis.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

From the raw data fixations, fixations with a minimum duration of 100 milliseconds were calculated. Fixations were then used to compute dwell times. A dwell time is the amount of time the participant paused on an AOI. At this stage the data was given to Cranfield University in Microsoft Excel (Excel) format together with the eye tracking and cockpit videos. Cranfield University then removed the fixations of under 200ms for any given AOI at one time since fixations under 200ms do not suggest that information is being actively processed (Yu et al., 2016). These data were analysed following the process detailed in Figure 52 to develop participant timelines described in section 2.10.5.

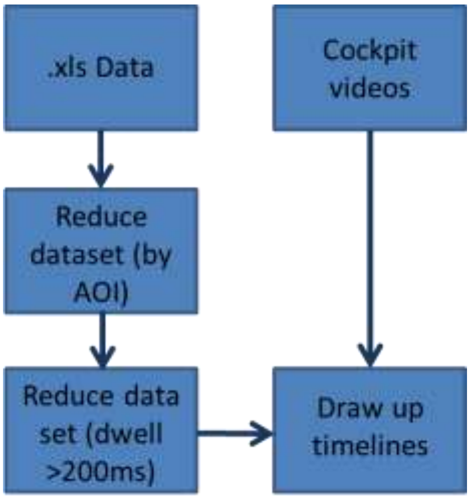


Figure 52: Data processing procedure for AOI timeline generation

A deep-dive analysis was carried out for pilot 6 to propose SA insights, following the process detailed in Figure 53. Data from two participants (36 and 39) was excluded due to AOI calibration errors.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

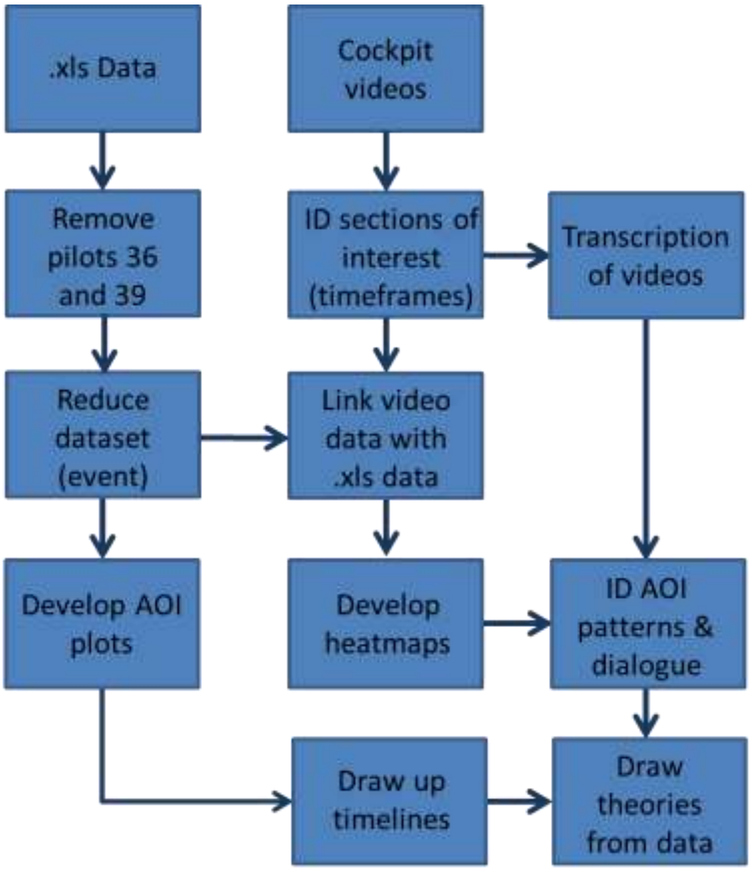


Figure 53: Data processing procedure for deep dive analysis

Areas of Interest for eye tracking analysis

Figure 54 shows the defined areas of interest for the second simulator experiment at Thales. Table 9 details the different AOIs.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

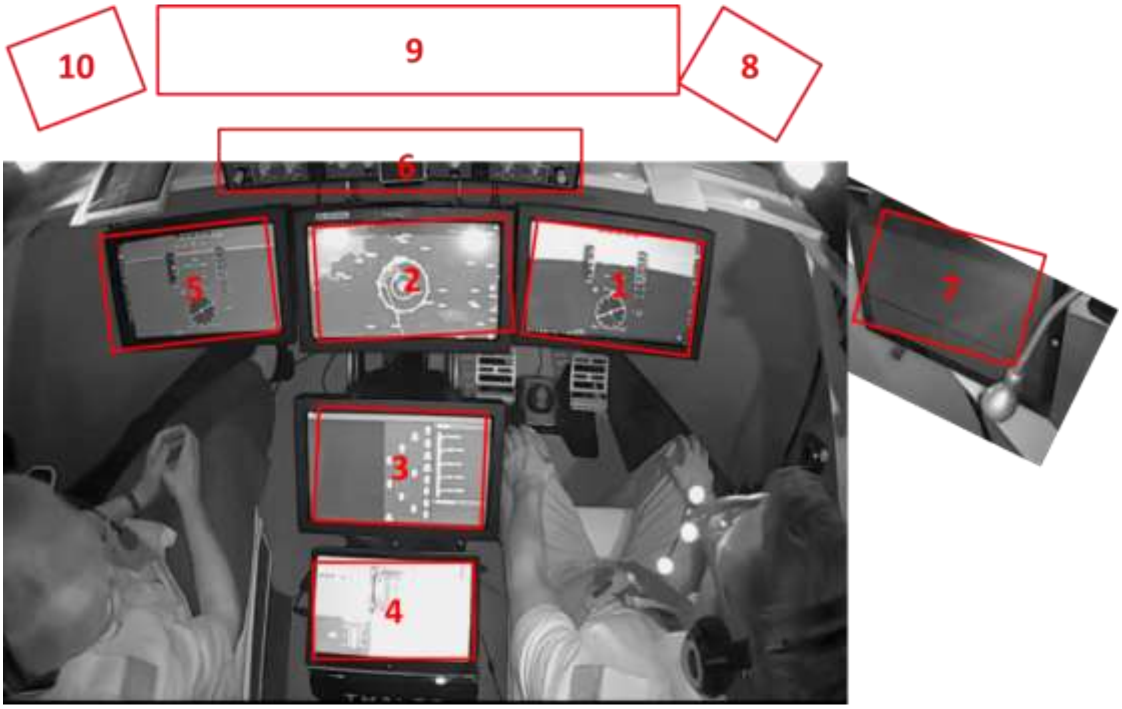


Figure 54: Areas of Interest

Table 9: Defined Areas of Interest

AOI	Acronym	Definition
1	PFD FO	Primary Flight Display First Officer
2	ND	Navigation Display
3	SD	Status Display
4	Pedestal*	Pedestal controls
5	PFD CPT	Primary Flight Display Captain
6	FCU	Flight Control Unit
7	EFB	Electronic Flight Bag
8	WINDOW RGT	Window Right
9	WSHLD	Windshield
10	WINDOW LFT	Window Left

*The Pedestal Contains:

- the thrust levers
- the lever for the speed brake
- the lever for the flaps
- the landing gear selector lever to select the landing gear up or down

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

- the landing gear indicator panel showing whether the gear is locked in the position selected by the gear selector lever
- the auto brake panel with the buttons to select the mode of the auto brake (LOW, MEDIUM, MAX)
- the antiskid and nose wheel steering selector button

2.10.5. Results

Pilot timelines

In this section the results will be presented in terms of time spent looking at each AOI, for each separate timeframe, as discussed in section 3.1. These will be presented firstly by participant (21 – 40), then by experimental step. Step 2 was completed by pilots 21-30, and step 3 was completed by pilots 31 – 40.

Due to the nature of the data, it did not meet the assumptions for parametric testing. Therefore Mann-Whitney U-tests were carried out to explore the data, specifically differences between steps 2 and 3.

Differences between pilots for time frame 1

This timeframe covers all activities from the onset of the AC bus failure, to the end of the limitations. Figure 55 shows the time spent looking at each AOI by each pilot from timeframe 1. Figure 56 shows the time spent looking at each AOI by condition (step 2 and step 3).

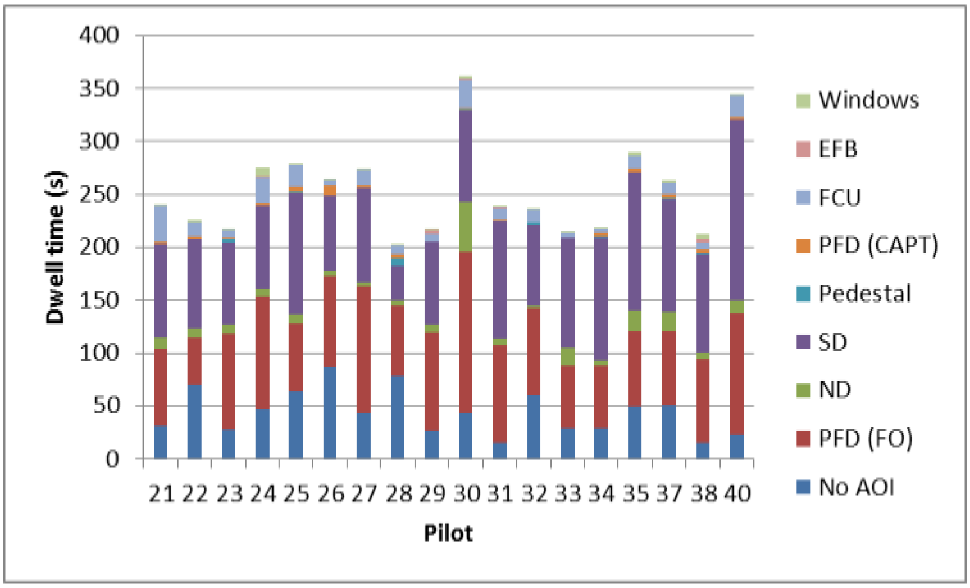


Figure 55: Timeframe 1 by pilot

The total time taken to complete the tasks in timeframe 1 Ranged from 202 seconds for pilot 28, to 361 seconds for pilot 30. The mean time was 253.8 seconds (n=18, SD=44.7). Typically, the pilots spent most of their time focussing on their PFD, and the SD. Pilots 30 and 40 spent longer to complete the tasks in timeframe 1 than the other 16 pilots. Pilots 30 and 40 will be used for the deep dive analysis in section 2.10.6.

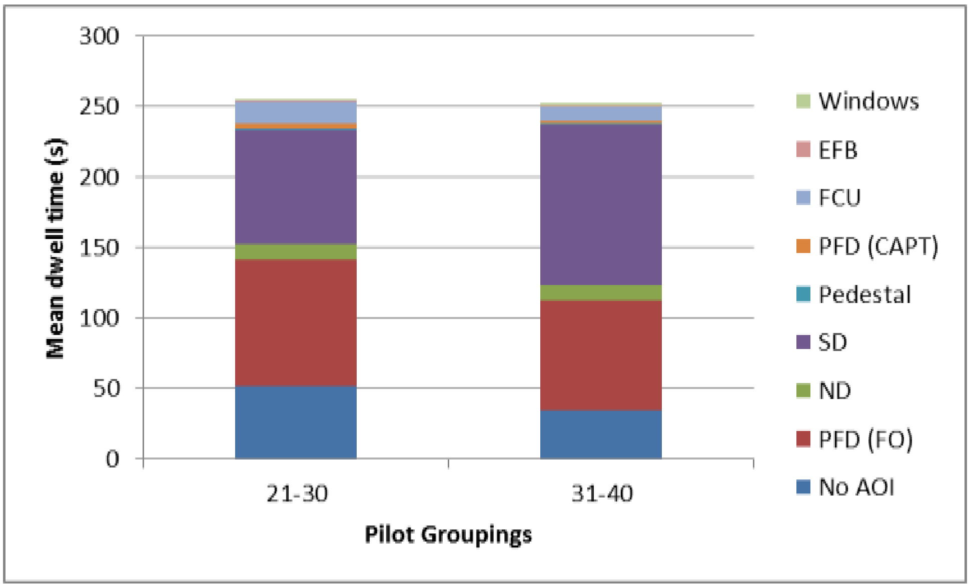


Figure 56: Timeframe 1 by step

The data did not meet the assumptions for a parametric test. A Mann-Whitney U-test revealed that the distribution of total mean dwell times was the same across step 2 (pilots 21-30) and step 3 (pilots 31 – 40). The time the pilots spent looking at the SD was significantly higher in step 3 than step 2 ($U=12$, $p=.012$). The comparisons for all other AOI's were not significant.

Differences between pilots for time frame 1a

This timeframe covers all activities from the onset of the AC bus failure, to the completion of the ECAM actions. Figure 57 shows the time spent looking at each AOI by each pilot from timeframe 1a. Figure 58 show the time spent looking at each AOI by condition (step 2 and step 3).

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

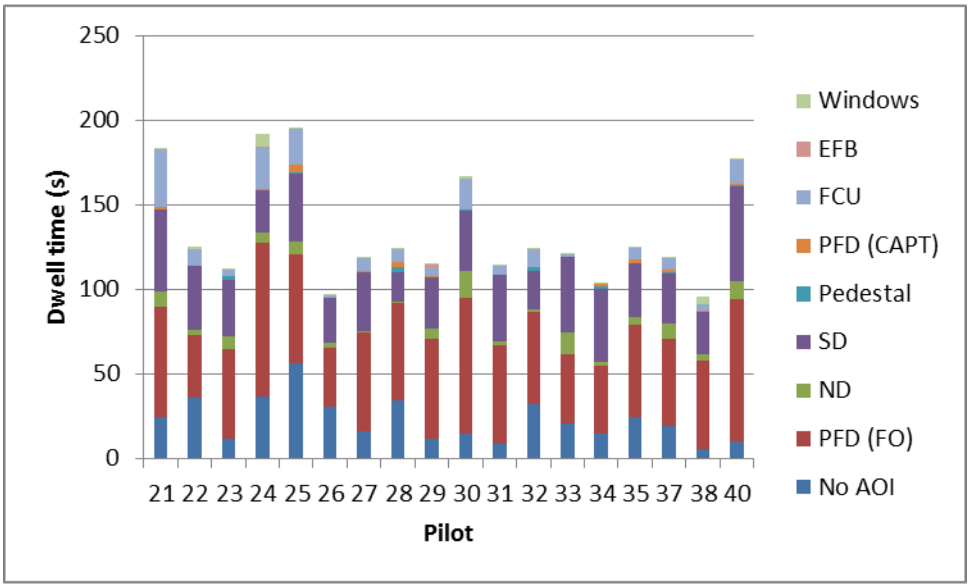


Figure 57: Timeframe 1a by pilot

The total time taken to complete the tasks in timeframe 1a Ranged from 96 seconds for pilot 38, to 195 seconds for pilot 25. The mean time was 133.8 seconds (n=18, SD=32.9).During this timeframe, the AOI receiving the most attention is the PFD (FO). Pilots 21, 24 and 25 took the longest to complete the tasks in this timeframe. These pilots had an ATC interruption during this timeframe, which would also explain the increased time looking at the FCU. Pilots 26 and 38, who took the shortest time to complete the tasks, did not receive interruptions. Pilot 38 will be used for the deep dive analysis in section 2.10.6.

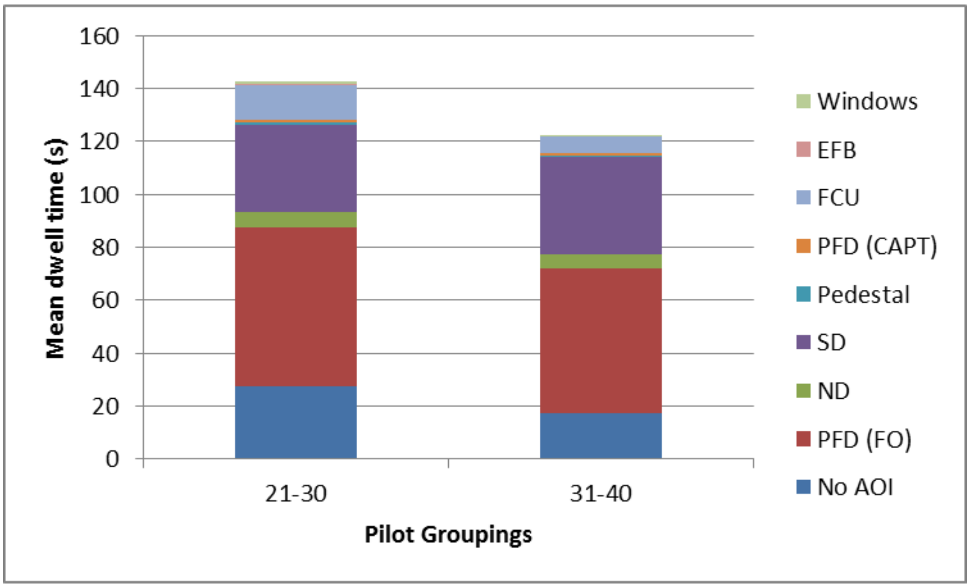


Figure 58: Timeframe 1a by step

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

A Mann-Whitney U-test revealed that the distribution of total mean dwell times was the same across step 2 (pilots 21-30) and step 3 (pilots 31 – 40). The comparisons between mean times for the individual AOI's were not significant.

Differences between pilots for time frame 1b

This timeframe covers all activities for the duration of the limitations. Figure 59 shows the time spent looking at each AOI by each pilot from timeframe 1b. Figure 60shows the time spent looking at each AOI by condition (step 2 and step 3).

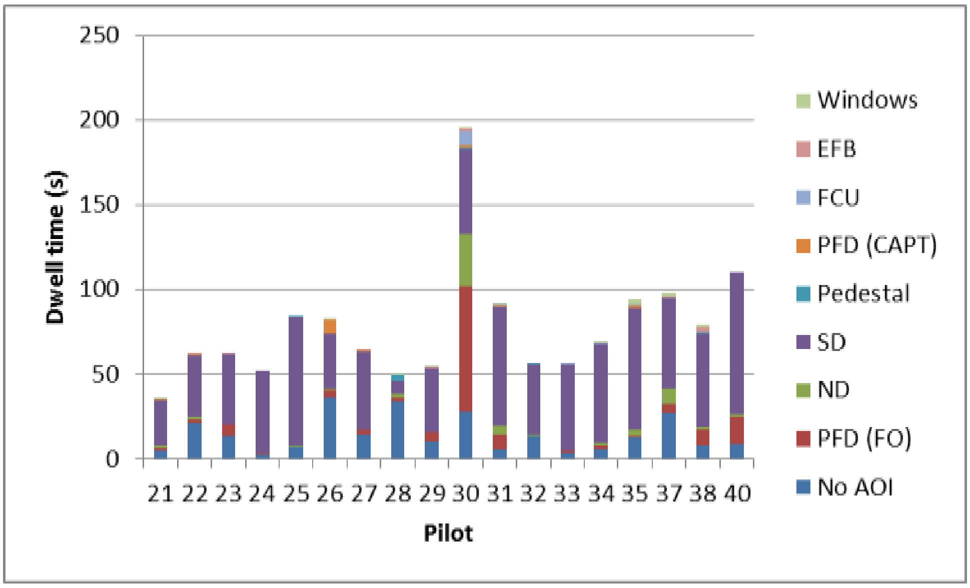


Figure 59: Timeframe 1b by pilot

The total time taken to complete the tasks in timeframe 1b Ranged from 35 seconds for pilot 21, to 195 seconds for pilot 30. The mean time was 77.4 seconds (n=18, SD=35.3). During this step we would expect the gaze to be focussed on the SD for the majority of the time. This was observed for most of the pilots, with the exception of pilot 30, who spent the majority of their time during this task looking at their PFD. This can be attributed to the fact that pilot 30 received an ATC interruption during the limitat ions. Taking the least amount of time to complete these actions is pilot 21. It was observed that the captain completed these, rather than the FO. It was also observed that pilot 26 spent more time than anyone else looking at the captains PFD during this time. Pilots 21 and 26 will be used for the deep dive analysis in section 2.10.6.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

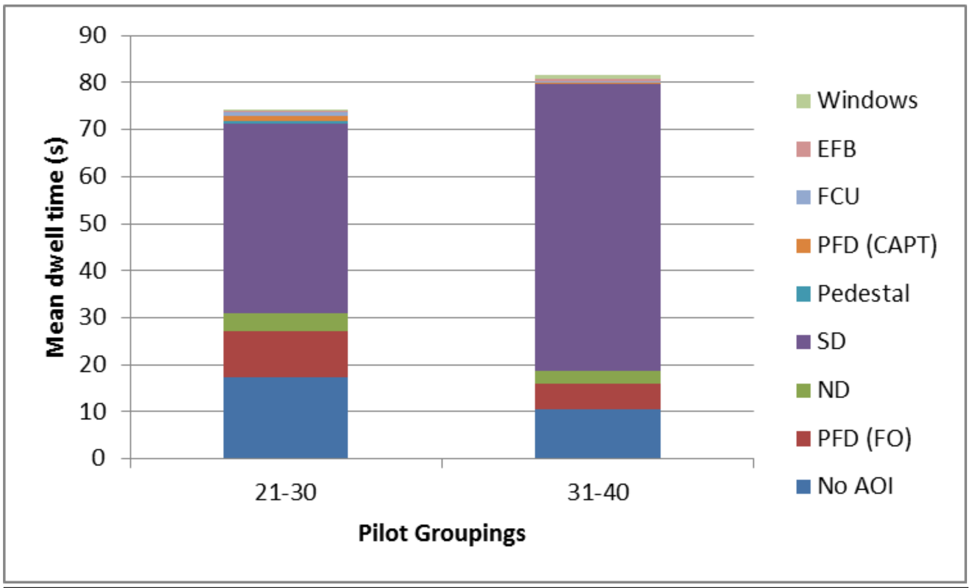


Figure 60: Timeframe 1b by step

A Mann-Whitney U-test revealed that the distribution of total mean dwell times was the same across step 2 (pilots 21-30) and step 3 (pilots 31 – 40). The time the pilots spent looking at the SD was significantly higher in step 3 than step 2 (U=10, p=.006). The comparisons for all other AOI's were not significant.

Differences between pilots for time frame 2

This timeframe covers all activities from the end of limitations to touchdown. Figure 61 shows the time spent looking at each AOI by each pilot from timeframe 2. Figure 62 shows the time spent looking at each AOI by condition (step 2 and step 3).

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

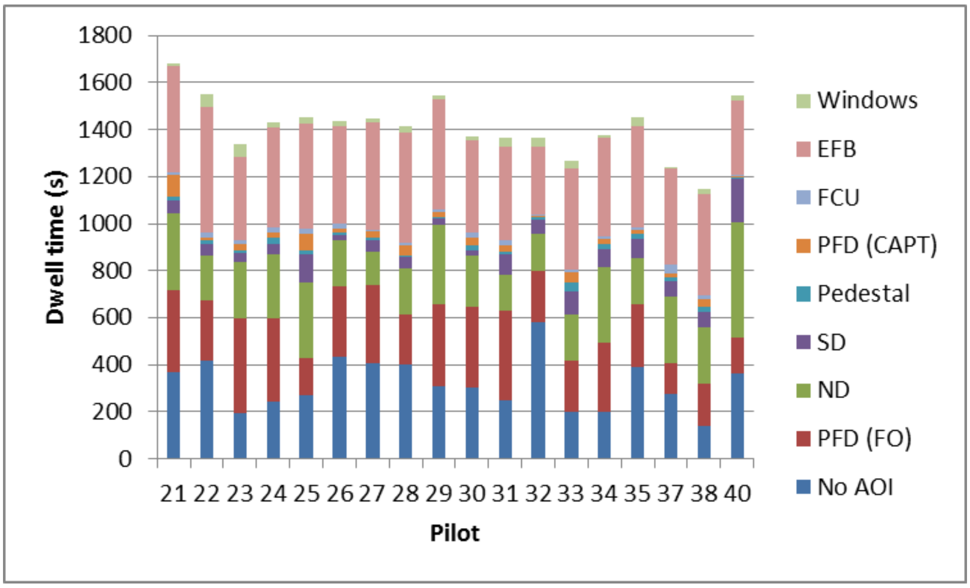


Figure 61: Timeframe 2 by pilot

The total time taken to complete the tasks in timeframe 2 ranged from 1145 seconds for pilot 38, to 1683 seconds for pilot 21. The mean time was 1412.1 seconds (n=18, SD=126). The AOI that the pilots focussed on the most for this segment is primarily the EFB. This is understandable as the tasks for this timeframe included carrying out a LAPA calculation for runway 09.

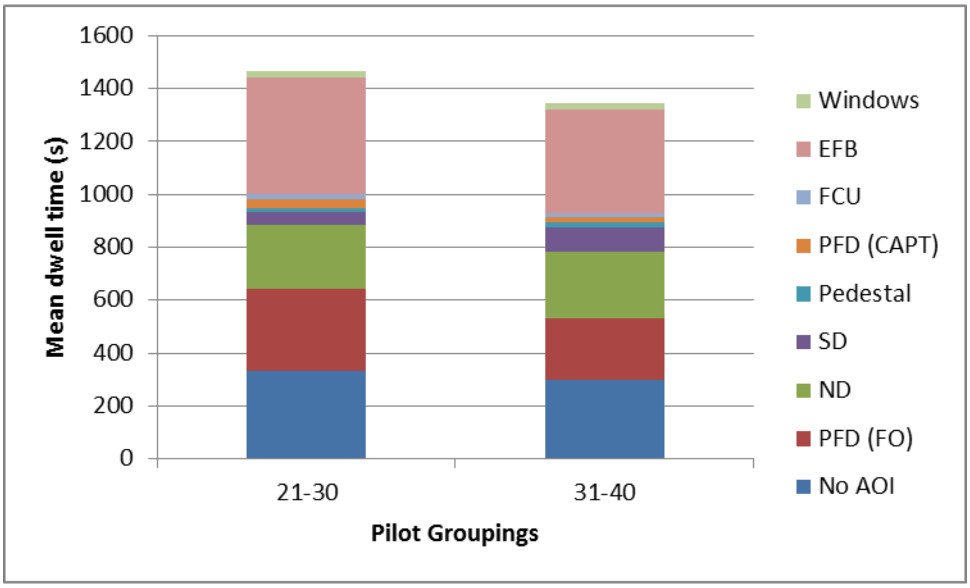


Figure 62: Timeframe 2 by step

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

A Mann-Whitney U-test revealed that the distribution of total mean dwell times was the same across step 2 (pilots 21-30) and step 3 (pilots 31 – 40). The time the pilots spent looking at the SD was significantly higher in step 3 than step 2 ($U=7$, $p=.002$). The comparisons for all other AOI's were not significant.

Overall, the times taken to complete the tasks in each of the timeframes did not differ significantly between steps 2 and 3. However, although not statistically significant, the pilots in step 2 typically took longer to complete the tasks in timeframe 1a, and the pilots in step 3 typically took longer to complete the tasks in timeframe 1b. This became approximately equal across the entirety of timeframe 1. This could be attributed to the extra information and input that the AV2020 system with improvements (step 3) required to be able to complete the limitations in timeframe 1b. The AV2020 system used in step 3 is designed to assist the pilots during failures, by representing the reachable range on the ND, along with information regarding runways and airports.

Interestingly, for all timeframes apart from 1b, the time the pilots spent looking at the SD was significantly higher for step 3 than step 2. This will be explored further in the deep dive analysis.

2.10.6. Deep dives

Five pilots (participant numbers 21, 26, 30, 38 and 40) were selected for the deep-dive analysis. Pilot 26 was identified as a poorer performer, and pilot 38 one of the better performers in the simulations. The full transcriptions for timeframe 1 for these pilots can be found in Appendix A. The key findings only will be detailed in this section and bespoke 'heatmaps' and 'timeplots' have been developed to assist in visualisation of the data. The 'heatmaps' and 'timeplots' have been generated using Mathworks MATLAB (MATLAB). The bespoke code developed for this analysis can be found in appendix B.

The heatmaps display the relative amount of time the FO spent looking at an AOI. The diameter of the red circles on the diagrams are proportional to the amount of time spent looking at the AOI. This time has been normalised to the simulation timeframe. Any time the FO spent not focussing on an AOI has been displayed as arrows if this occurs between AOIs. Any other time not focussed on the AOI's has not been included in the heatmaps. The timeplots show the number of fixations and their distribution on each AOI across the timeframe under consideration.

The majority of detailed analysis is carried out for timeframe 1, as this was deemed to be richer in terms of interaction with the interface given the scenario content.

Key events and dialogue for timeframe 1

One of the poorer performers for the scenario, pilot 26, took longer to complete the tasks in timeframe 1 than many of the other pilots. Pilot 26 also spent more time than any other pilot looking at the captains PFD during this phase. Figure 63 shows that the pilot spends a lot of time switching between his PFD, and the captains PFD, as well as the SD. One explanation is that the pilot is looking for re-assurance from the

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

captain at around 1600s into the scenario, as can be seen by Figure 64. This coincides with the captain making a mistake when completing the limitations:

Captain: “I’m sorry, I have made a mistake. Oops. I made a new mistake. No, it’s coming back, so disregard. Okay.”

The pilot then checks the SD to ensure all is correct.

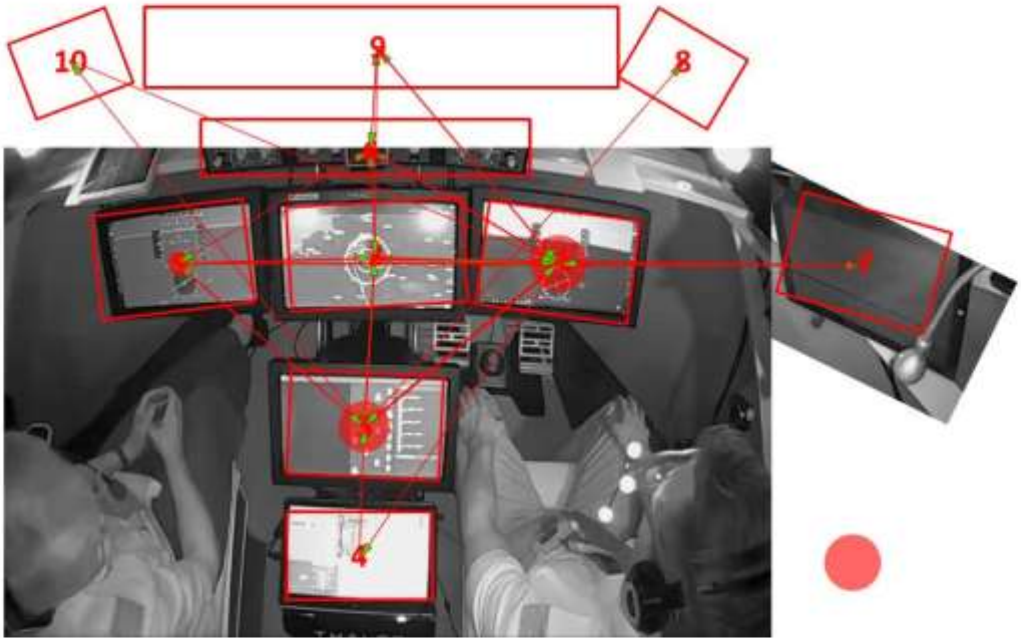


Figure 63: Heatmap Pilot 26 timeframe 1

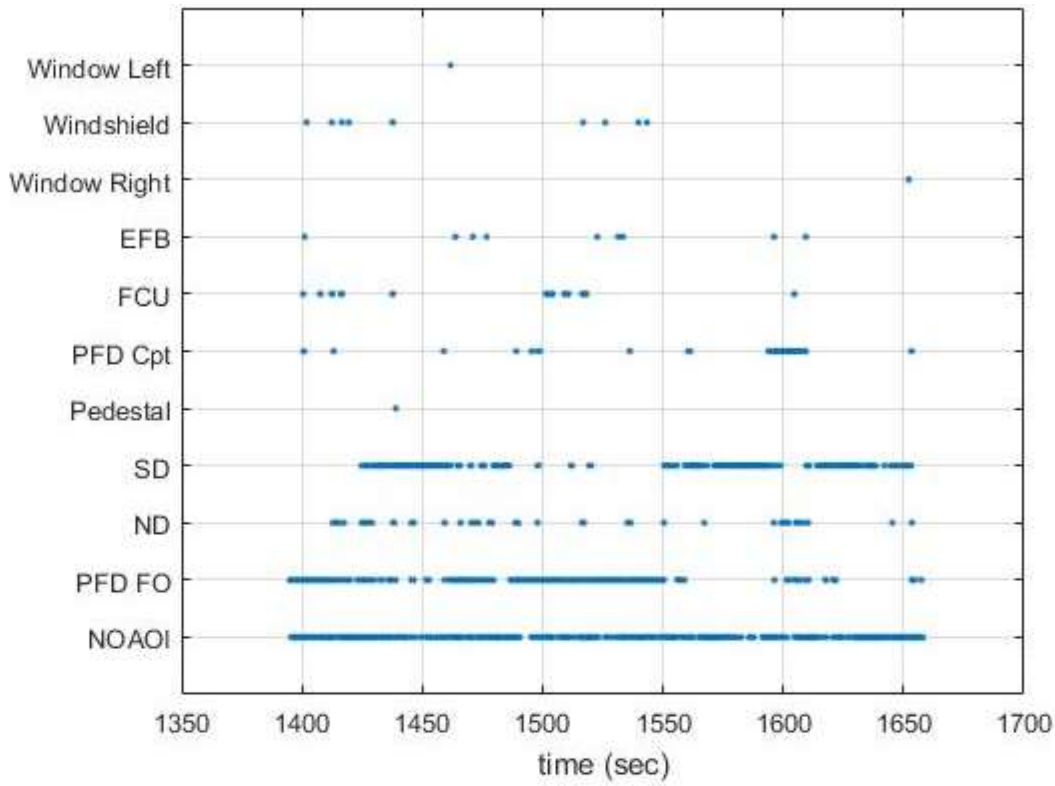


Figure 64: Timeplot Pilot 26 timeframe 1

In contrast pilot 38, classed as a good performer, took a relatively short amount of time to complete the tasks in timeframe 1. This is reflected in the dialogue, in which pilot 38 asks short questions, and is getting a clear answer from the captain, backed up by the pilots own PFD. This is again double checked by referencing the ND and SD, which can be seen in Figure 65.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

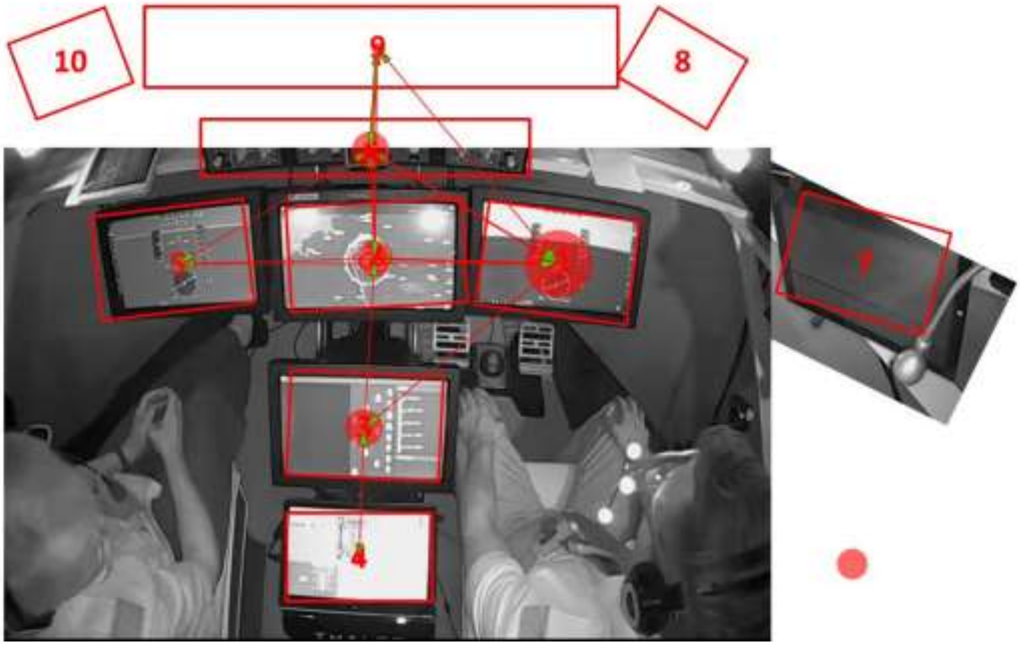


Figure 65: Heatmap Pilot 38 timeframe 1a

Pilot 38 can be clearly seen to be focussing on their own PFD for short amounts of time, intersp ersed with the ND (see Figure 66).

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

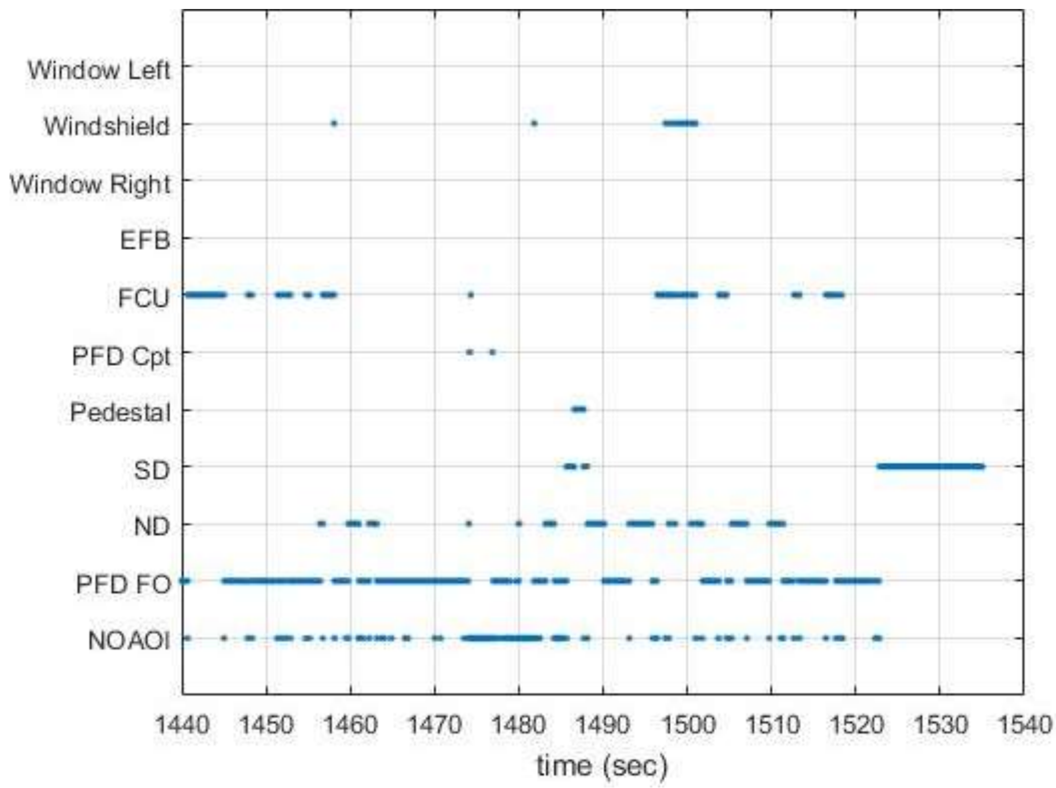


Figure 66: Timeplot Pilot 38 timeframe 1a

Neither pilot 26 nor pilot 38 had noticed the fuel was low by this point. Pilots 21 and 30 noticed the low fuel prior to the AC bus fault. During the AC bus fault and the subsequent actions, both pilots had awareness that the fuel was going to be an issue. Pilot 21:

FO: "Okay. Fuel on board is now 1,500 now. Yeah, I'll tell him new approach. Lufthansa 2487 requesting approach".

This was noticed by pilot 21 just over 8 minutes into the scenario. Pilot 30 noticed the fuel around 10 minutes into the scenario, which may help in explaining the long amount of time to complete the ECAM actions during timeframe 1a and the length of time that they focussed on their PFD (Figure 67).

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

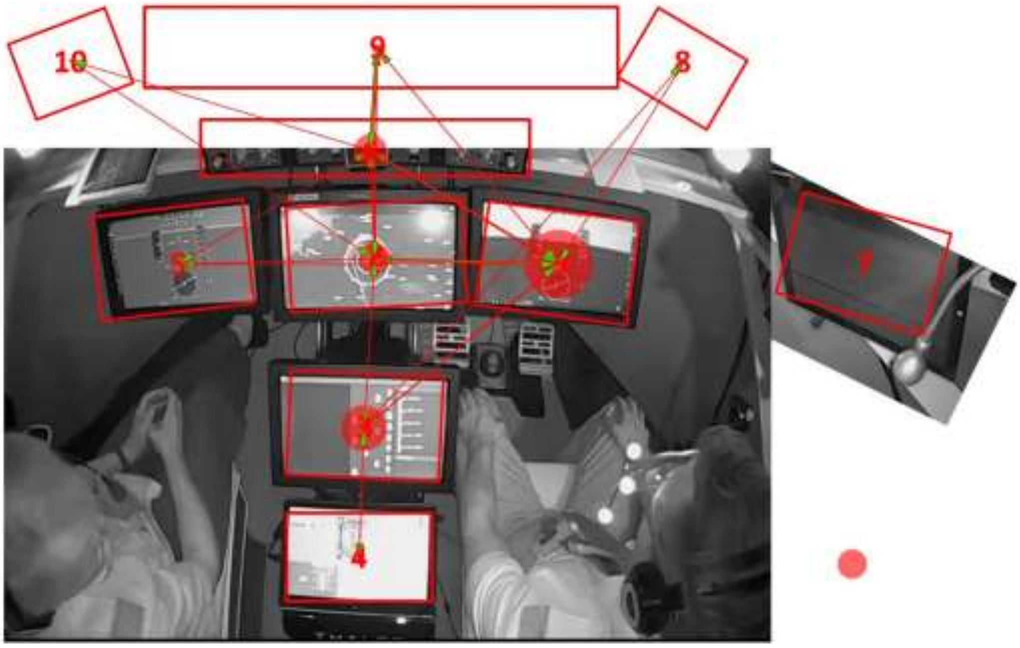


Figure 67: Heatmap Pilot 30 timeframe 1a

Pilot 30 also keeps referring back to the fuel situation during the AC Bus 1 fault, which may indicate that he has good awareness of the situation. This can be observed in Figure 68.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

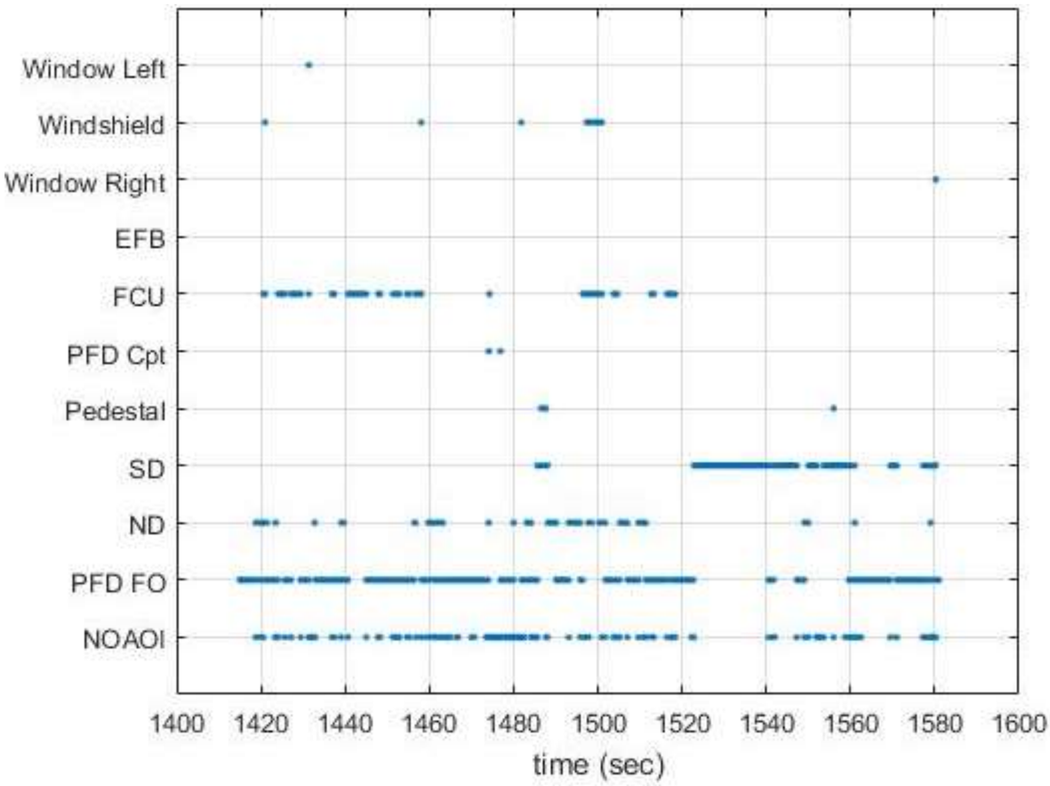


Figure 68: Timeplot Pilot 30 timeframe 1a

The pilot notes at time (Figure 68) 1490 that the "Fuel situation's a little bit critical, 1.5." This information is acquired from the ND, feeding into the understanding of the current situation. Pilot 30 also spends the longest amount of time completing the tasks in timeframe 1b, spending a considerable amount of time checking the ND. The audio indicates that the captain and pilot 30 spent time during 1b future planning. This is not indicated to this degree by any other pilot, which may start to explain the length of time to complete the limitations.

During timeframe 1, the better performers spent the majority of their time focussed on their own PFD, then checking information with the captain using concise instructions. They then confirmed this by checking the ND and SD to ensure the fault had cleared and the limitations completed by the captain. In contrast to the first simulation at DLR, the FO's during this simulation appear to be leading the decision making, whereas a key finding of the DLR simulation was that the FO was offloading their SA requirement to the captain. The dialogue and the eye tracking data would indicate that the FOs are using the displays more, rather than asking the captain for confirmation regarding events and decisions.

There did not appear to be a difference in behaviours between step 2 and step 3 for timeframe 1, and there was not a clear difference between the timing of the fuel awareness between the steps either.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

Key events and dialogue for timeframe 2

Pilot 26 noticed the fuel situation six minutes after the completion of the limitations. Although pilots 21 and 30 noticed the fuel early, they did not declare mayday until eight minutes after limitations (pilot 21) and 2 minutes after limitations (pilot 30).

Pilot 26 appears to still be looking for reassurance from the captain's PFD, even though the FO is leading the task (Figure 69). This appears to have knock-on effects for pilot 26, who need to be prompted to request a different runway due to lack of fuel.

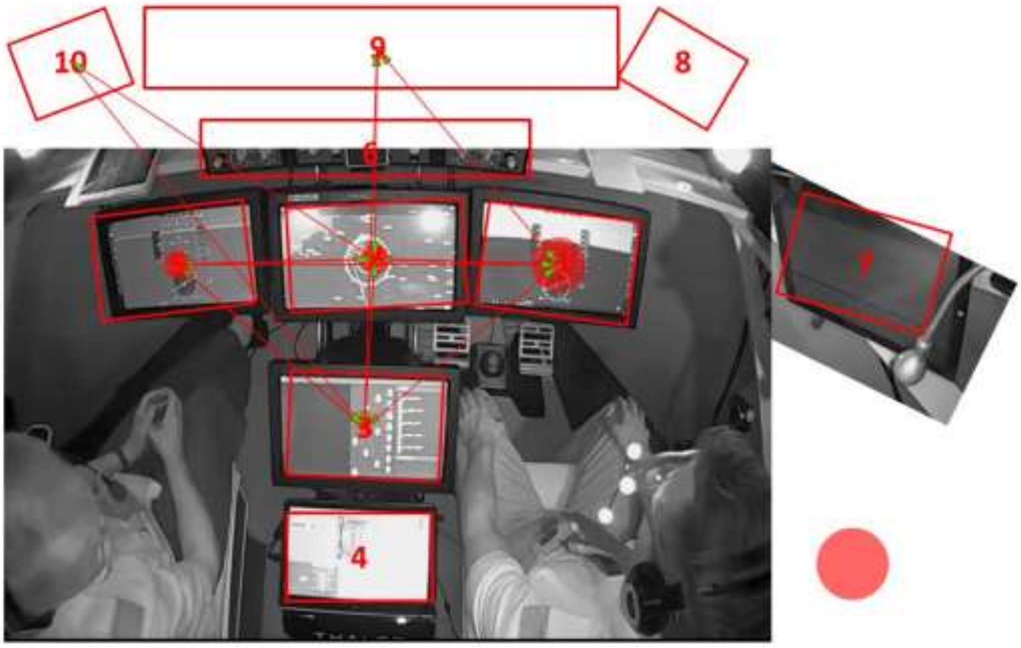


Figure 69: Heatmap Pilot 26 timeframe 2 from fuel awareness to mayday

The EFB is used a lot during timeframe 2, which is explained by the need to carry out LAPA calculations. This can clearly be seen in Figure 70 which depicts the heatmap for timeframe 2 for pilot 30.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

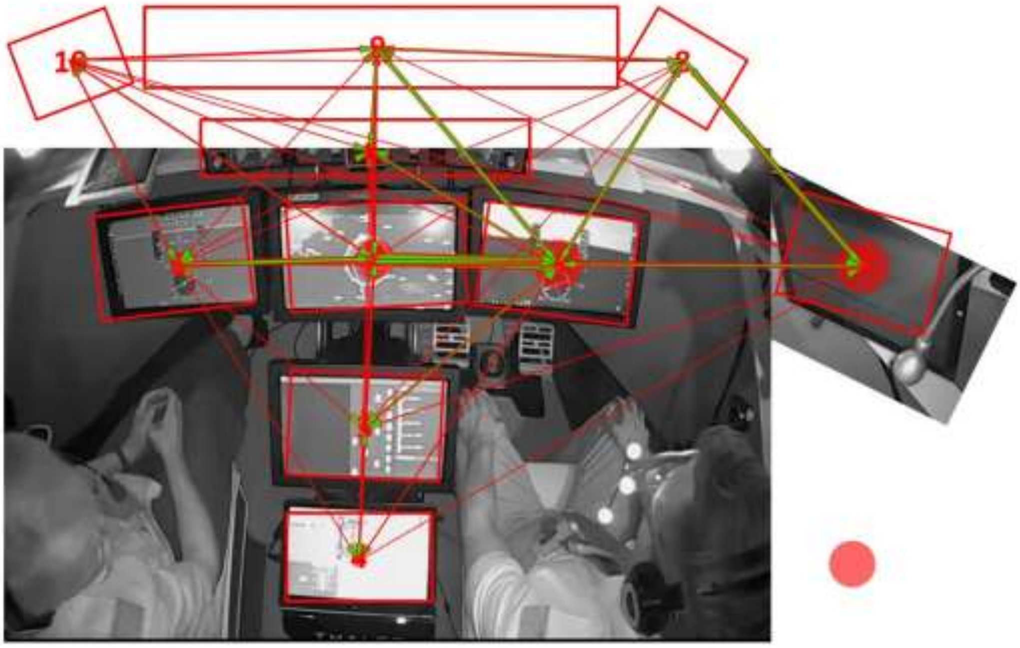


Figure 70: Heatmap Pilot 30 timeframe 2

Figure 70 clearly displays that the EFB is being looked at the most by pilot 30 during this timeframe, and for longer periods (Figure 71), which align with the LAPA calculation and the completion of the landing checklist.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

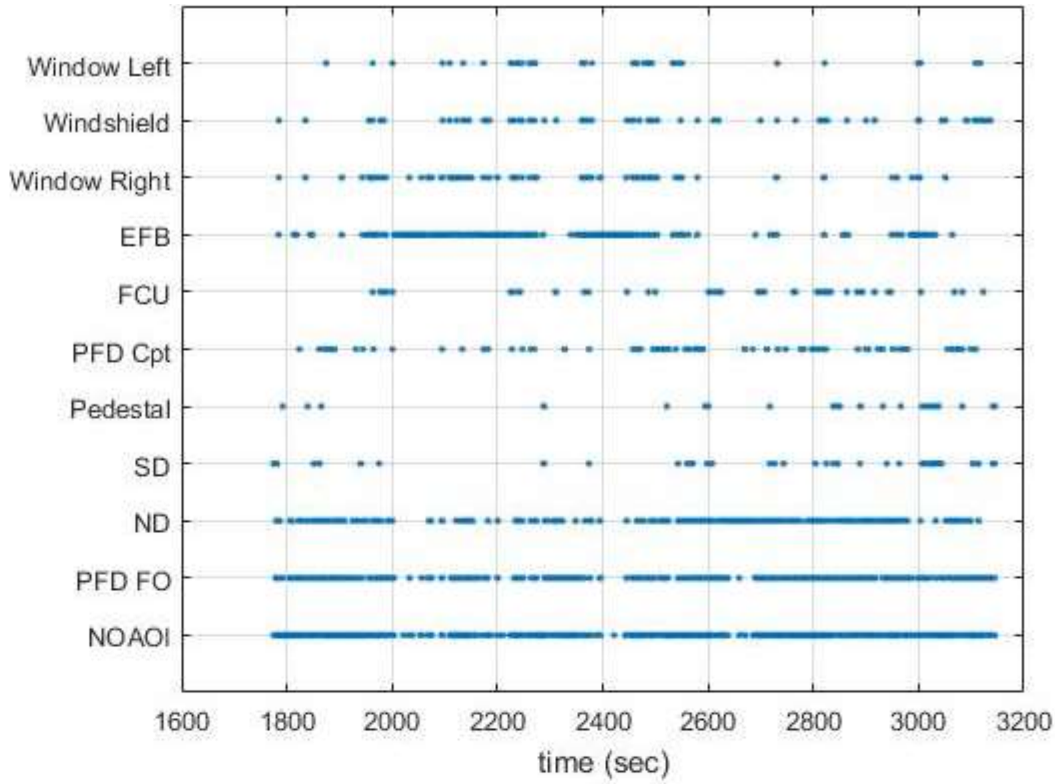


Figure 71: Timeplot Pilot 30 timeframe 2

There does not appear to be a difference in eye movement behaviours between steps 2 and 3 for timeframe 2, and the tasks are carried out routinely for each pilot.

2.10.7. Discussion

The analysis of the eye tracking data and the cockpit dialogue was able to identify how SA was shared between the captain, the FO, and the AV2020 interface and how this was managed. In most cases, the FO initiated cross checking with the Captain. At a surface level this would indicate that the FO had better SA than the captain, in contrast to the first simulation where the opposite was true.

This may indicate that the pilots had a better awareness of their situation, and this may be attributed to the improved information provision on the interface. The FO spent the majority of their time focussed on their SD during timeframe 1, which indicates that the system information was being obtained directly from the display, leading to level 2 SA. A clear difference between this simulation and the previous simulation at DLR was the proactive approach of the FO in this simulation, compared to the reactive approach in the previous simulation.

Although level 3 SA was effectively 'engineered' by the step 3 Thales system, it still required the FO to acknowledge the information. In most cases, the additional information made little difference to the

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

handling of the situation in a general sense. However, it was clear from the dialogue that the pilots in step 3 were able to establish work plans with more efficiency than in step 2, by freeing cognitive resource.

In the previous simulation, captain SA was supported by external information being fed directly to him, in addition to observing the FO's actions and monitoring the instruments. The FO's SA was supported by the information being fed to him by the captain, along with his own instruments. They were using different information, which as a result built different mental models. During this simulation, the interface appeared to support both pilots more effectively, through having access to the same information.

Pilots had a better comprehension (level 2 SA) during this simulation than the previous simulation. This finding is supported by the heatmaps and the dialogue analysis. The FO was able to comprehend the information directly from the interface due to the added information on the PFD, rather than having to calculate it. This was also apparent in the reduction in the amount of time the FO's spent referring to their EFBs, especially during timeframe 1.

2.10.8. Exploitation for project

This proof of concept has demonstrated that this type of approach to eye tracking analysis can be valuable in giving insight into the SA of the eye tracking wearer. This enables certain inferences about the information that is important, and what is comprehended and carried forward to be made.

The main limitation of this analysis was the lack of BeGaze software, which meant the analysis was limited.

However, we believe that this type of analysis does add value, and the combination of the dialogue and the eye tracking data enables conclusions to be drawn.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

2.11. Timings

2.11.1. Results

Overview of the ECAM procedure:

Before the bus failure, the captain is the pilot flying. When the bus failure fault appears, the captain asks the FO to have control of the aircraft and the captain starts the ECAM actions. FO is the pilot flying.

In step 1, the captain strategy is to change control during the ECAM actions, as soon as he recovers his main displays. Then Captain is the pilot flying (with autopilot and auto thrust) and the FO continues the ECAM actions procedure.

For Step 2 and 3 the captain finishes the ECAM actions before to change control with the FO.

In all cases, the captain is the pilot flying for the review of the limitations which are read by the FO.

ECAM Actions:

For step 1, ECAM actions require to read actions on the SD panel (#15 on the next figure) and to move switches and make controls on the overhead panel (#1).

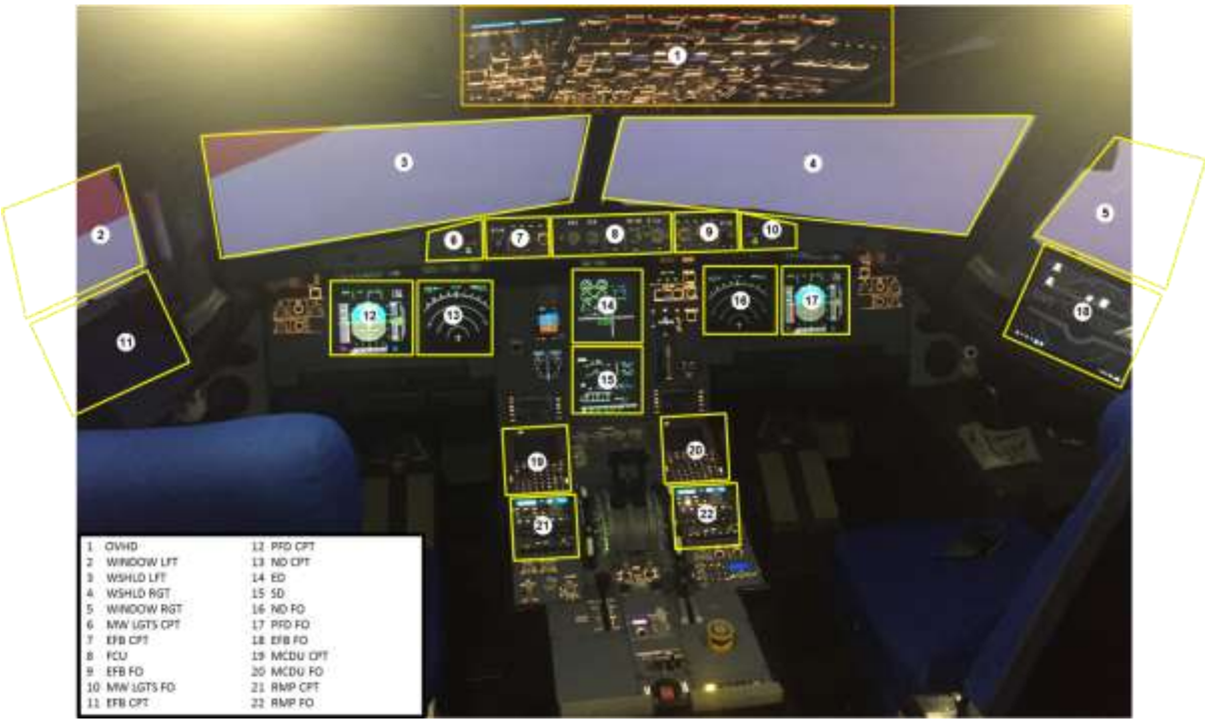


Figure 72: Panels on the DLR simulator

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

During the AC bus failure, panels #12, 13 and 14 are no longer available and the procedure is displayed on the SD panel as shown by the captain in Figure 73.

Figure 73: State of the display panels during the AC bus failure

Figure 74: Crew engaged in the ECAM action procedure

For step 2 and 3 all the actions and controls are made on the central system touch display.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

Figure 75: Crew engaged in the ECAM action procedure with the Thales new avionic interfaces. During the AC bus failure, the captain PFD is no longer available and the ECAM actions are managed thanks to the central system display

The immediate consequence is that the time required to go through the ECAM actions is much faster with the new interface.

Average duration of the ECAM actions (s):

- Step 1: 132.6 s
- Step 2; 75.5 s
- Step 3: 77.5 s

Two sample t-tests for a difference in mean (unpaired samples) indicate which differences are significant:

- Step 1 vs Step 2: [t(18)= 5.49; p=0.00003] - significant
- Step 1 vs Step 3: [t(18)= 4.60; p=0.0002] - significant
- Step 2 vs Step 3: [t(18)= 0.23; p=0.82] – not significant

These results are summarized by Figure 76.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

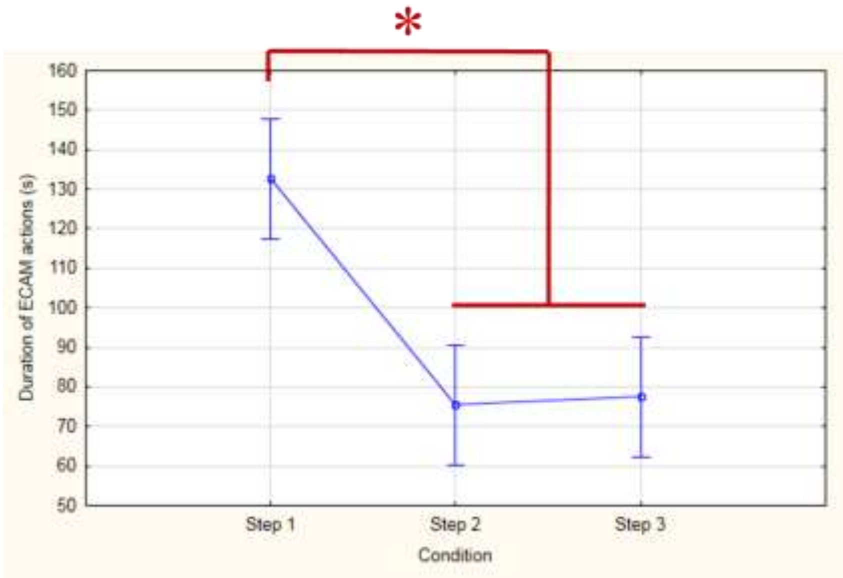


Figure 76: Duration of ECAM actions by conditions. Blue dots represent the mean duration of ECAM actions by condition; blue line segments represent the confidence intervals at 0.95

Review of the aircraft status

For step 1, the status of the aircraft is mainly assessed thanks to the SD display, while for steps 2 and 3 the status is displayed on the Central system screen. The next figures show the three configurations. The presentation of the information is not the same in the three cases.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

Figure 77: Status information on the SD display for step 1

Figure 78: Status information on the system central display for step 2

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

Figure 79: Status information on the system central display for step 3

If we compare the time required to go through the status review we have the following results.

Average duration of the status review process (s):

- Step 1: 53.0 s
- Step 2; 55.7 s
- Step 3: 79.2 s

Two sample t-tests for a difference in mean (unpaired samples) indicate which differences are significant:

- Step 1 vs Step 2: [t(18)= 0.52; p=0.61] – not significant
- Step 1 vs Step 3: [t(18)= 4.00; p=0.0008] – significant
- Step 2 vs Step 3: [t(18)= 3.28; p=0.004] –significant

These results are summarized by Figure 80.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

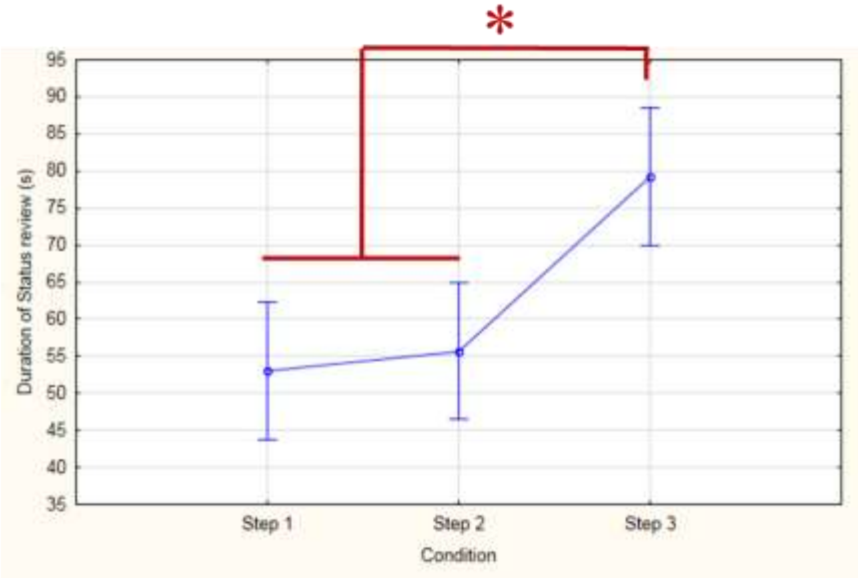


Figure 80: Duration of status review by conditions. Blue dots represent the mean duration of status review by condition; blue line segments represent the confidence intervals at 0.95

Also, while the new presentation of the information as made in step 2 does not significantly modify the time spend to review the aircraft status and limitations, the choices made for step 3 significantly increase the time spent by the crew to review the aircraft status. This result can be counter-intuitive, but it reflects that the crew better take into consideration the consequences of the limitations in the step 3 and so include in the review more discussions to anticipate further situations.

2.11.2. Discussion

The analysis of the timings for ECAM actions clearly indicates that the new interface speed up the process. In step 2 and 3 the crew spent fewer time than in step 1 to complete the required actions. With the new interface the process indications, the actions required and the elements to check are nearly all located on the same screen and the crew is then more efficient. The actions are easier to made (on the touchscreen) and more intuitive and the captain is more prone to do them by himself. The new interfaces modify also the cooperation between the captain and the first officer.

The difference between step 2 and step 3 can be seen on the time used to review the aircraft limitations. While the time requires reviewing limitations in steps 1 and 2 are equivalent, the time spent by the crew on that task is step 3 is much longer. Also it looks like the addition of a list of limitations for the landing in front of each inoperativ systems modifies the behavior of the crew. As stated previously, it was clear from the dialogue that the pilots in step 3 were able to establish work plans with more efficiency than in step 2. Also the display of the limitations linked to the inoperative systems encourages the projection of future status, so a higher level of situation awareness. But that step requires more time.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

2.12. Pilot competency evaluation

2.12.1. Method

A tool was used allowing web-based competency ratings by a group of airline flight training instructors. It showed video recordings of the simulation trials and it prompted them to rate the pilot monitoring's performance. Three phases were distinguished for analysis by the instructors:

- Approach into Bremen -This phase begins at the beginning of the scenario, and ends when the AC BUS 1 FAULT appears.
- AC BUS 1 FAULT - This phase begins when the AC BUS 1 FAULT appears, and ends when the crew receives the new ATIS K information.
- Wind shift: new ATIS K - This phase begins when the new ATIS K information is received by the crew, and ends at touchdown.

The instructors were to rate the pilot monitoring's performance on two competencies:

- Problem Solving & Decision Making;
- Situation Assessment.

On the following scale:

Rating given by instructor	Meaning of the rating	Presented in results as
Standard +	Exceeds behavioural marked description	3
Standard	As described	2
Standard -	Does not meet expectations, but not directly unsafe	1
Unacceptable	Not to standard, poses direct safety risk	0

Also the instructors checked behavioural markers that they saw the PM perform. The following markers could be checked for each phase:

Problem Solving and Decision Making	Situational Awareness
Searches actively for accurate and adequate info	Assesses accurately the a/c state and its systems
Identifies and verifies the cause of problems	Assesses accurately the a/c position and flight path
Employs proper problem-solving strategies	Assesses accurately the relevant environment
Works through problems without reducing safety	Keeps track of time and fuel

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

Makes appropriate and timely decisions	Maintains awareness of the performance of others
Sets priorities appropriately	Anticipates accurately and plans ahead
Identifies and considers options effectively	Develops effective contingency plans
Monitors, reviews, and adapts decisions as required	Identifies and manages threats effectively
Identifies and manages risks effectively	Responds effectively to indications of reduced SA
Improvises when appropriate	

Half of the experimental runs were performed with the step 2 interface and the other half with an improved interface (step 3) that was expected to better support the PM in de the scenario with the above mentioned competencies. The results of the performance with the step 2 and the step 3 are compared to test the above hypothesis.

To assess whether the step 3 HMI supported the pilots in the above mentioned competencies better compared to the step 2 HMI, the ratings were compared with a two tailed independent sample t-test, assuming equal variance.

Besides performance ratings the instructors selected Behavioural Markers they observed. These are presented in frequency charts. A Pearsons Correlation was calculated between the competency rating and the associated Behavioural Markers for each of the events and for the condition step 2 and step 3 separately.

Eight instructors rated the performance of the pilots in videos and checked the behavioural markers. Some of the videos were rated by multiple instructors, others by one instructor.

2.12.2. Results

The results of the average ratings for Problem Solving and Decision Making as given by the instructors are visualised in Figure 81, distinguishing different HMIs and the three phases.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

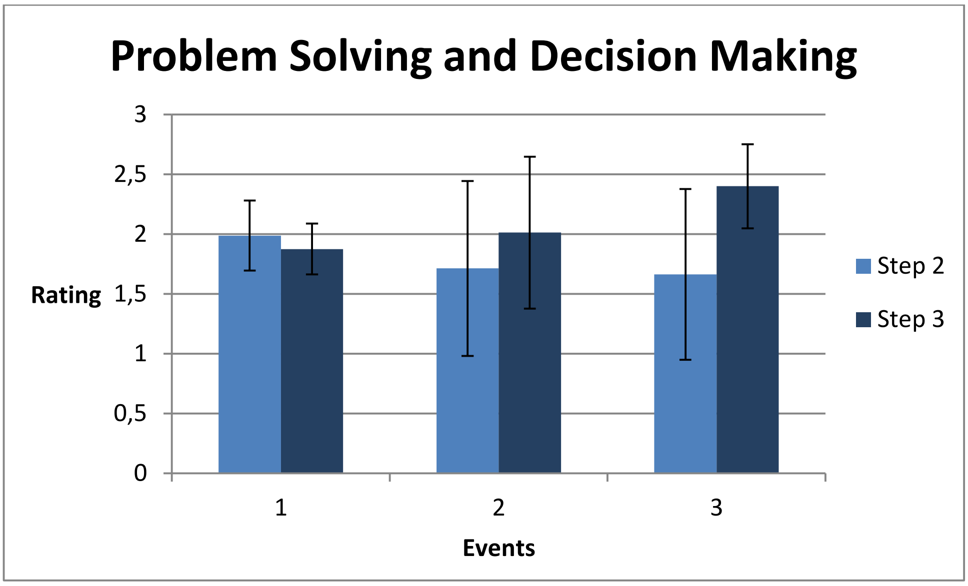


Figure 81: The ratings of the competency Problem Solving and Decision Making (n=10, error bars represent the 95% confidence interval)

The T-test did not reveal significant results between the runs with the step 2 HMI and the step 3. However, the performance on Problem Solving & Decision Making shows a trend for phase 3 (F=4.510, p=0.086), which might result from improvement in the step 3 HMI.

The average performance ratings for Situational Awareness are visualised in Figure 82.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

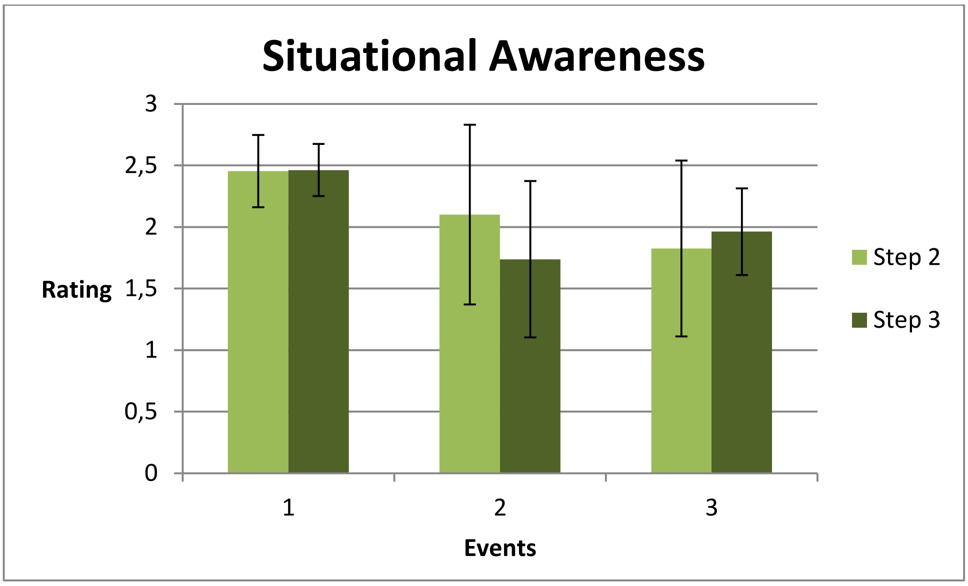


Figure 82: The ratings of the competency Situation Awareness (n=10, error bars represent the 95% confidence interval)

The differences in SA performance between the step 2 and the step 3 HMI are not significant.

The instructors selected the behavioural markers they observed for each phase. The results are presented in the next figures.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

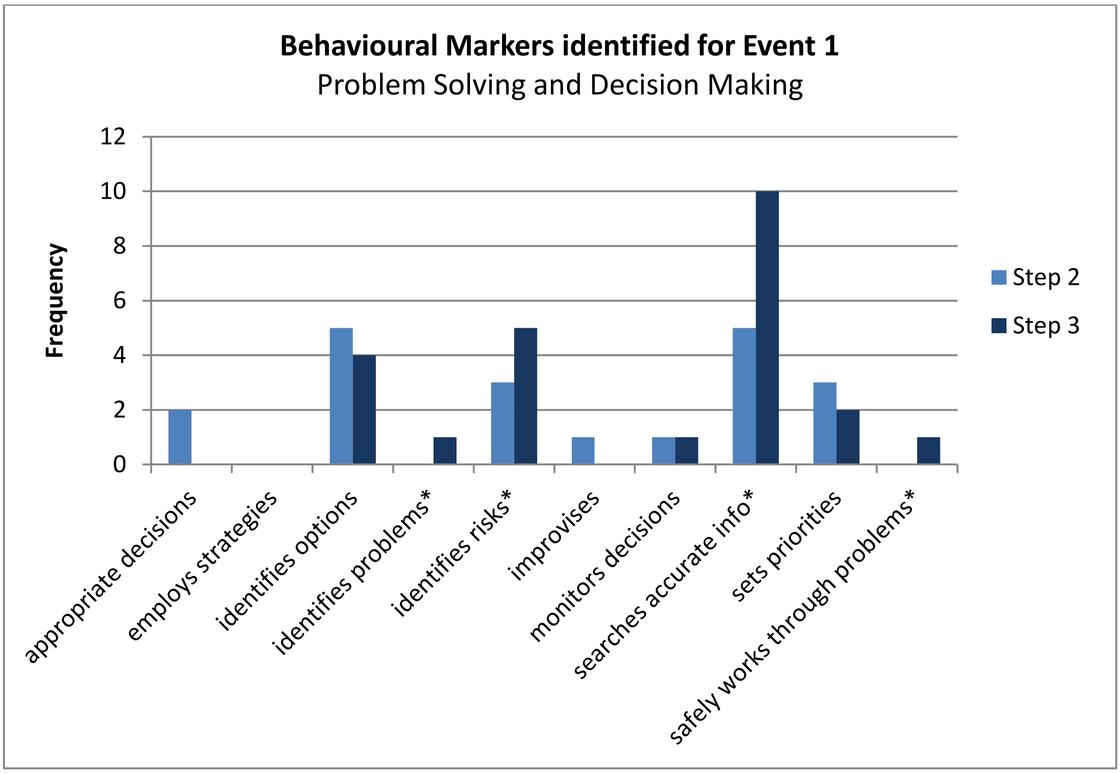


Figure 83: Behavioural Markers concerning Problem Solving and Decision Making selected for Phase 1 (n=10, * indicates a significant difference between step 2 and step 3 with 95% confidence)

Pearsons correlations show a significant result for **searching accurate info** with the PSDM performance (*r=.959, p<0.01*) considering the step 3 ratings only. This means that higher ratings for PSDM are associated with **searching accurate info** in case of phase 1 in the condition with the step 3 HMI. No correlations were considering the step 2 and step 3 conditions together.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

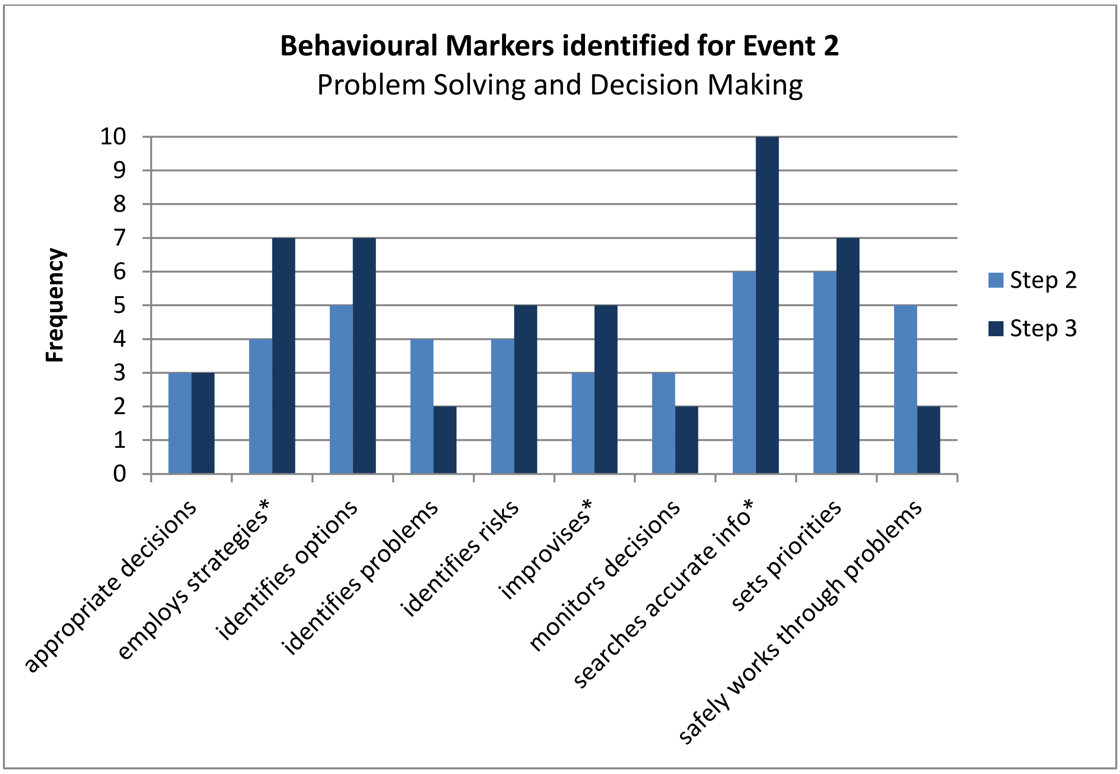


Figure 84: Behavioural Markers concerning Problem Solving and Decision Making selected for Phase 2 (n=10, * indicates a significant difference between step 2 and step 3 with 95% confidence)

Pearsons calculations for phase 2 considering the data from the step 2 runs and the step 3 runs together were made. Significant correlations were identified between performance ratings and behavioural markers: **identifying risks** (*r=.521, p=0.018*), **improvising** (*r=.492, p=0.028*), **monitoring decisions** (*r=0.511, p=0.021*) and **searching accurate info** (*r=0.47, p=0.036*). Higher performance ratings are associated with these behavioural markers.

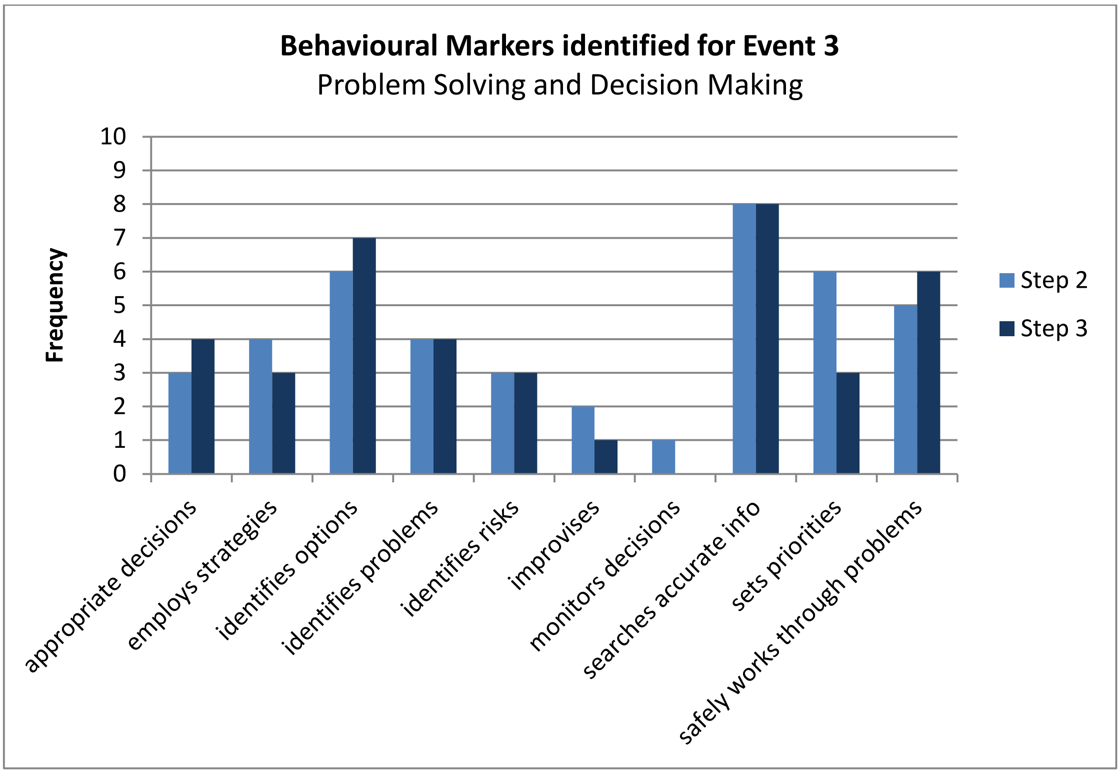


Figure 85: Behavioural Markers concerning Problem Solving and Decision Making selected for Phase 3 (n=10, * indicates a significant difference between step 2 and step 3 with 95% confidence)

No correlations were identified considering step 2 and step 3 together. However, a correlation exists between Problem Solving and Decision making and the Behavioural Marker **searching accurate info** for Phase 3, for step 2 (*r=0.761, p=0.011*).

The behavioural markers regarding situational awareness are displayed in Figure 86 to Figure 88.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

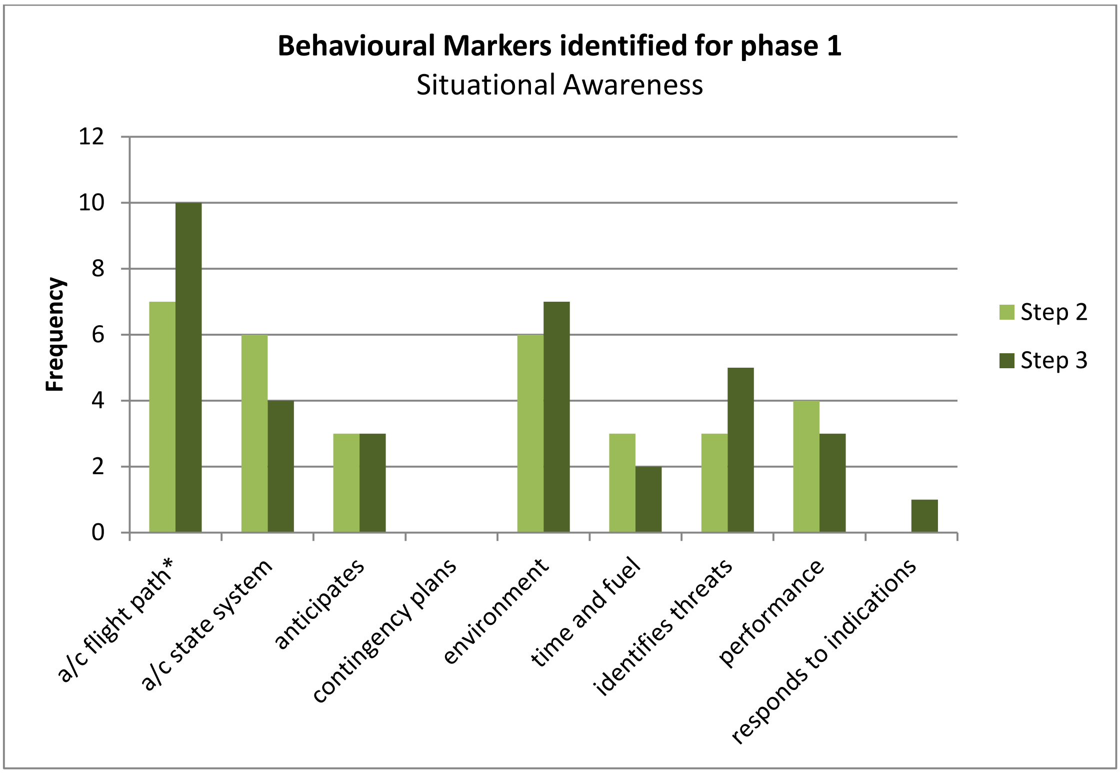


Figure 86: Behavioural Markers concerning Situational Awareness selected for Phase 1 (n=10, * indicates a significant difference between step 2 and step 3 with 95% confidence)

For phase 1, Pearsons correlation for Situation Awareness performance ratings with the associated behavioural markers shows a significant correlation for **identifying threats** (*r=0.561, p=0.01*). But it does not show significant differences between the two conditions.

In addition, considering only the step 2 data, **environment** and the SA performance correlate (*r=.833, p=0.001).*

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

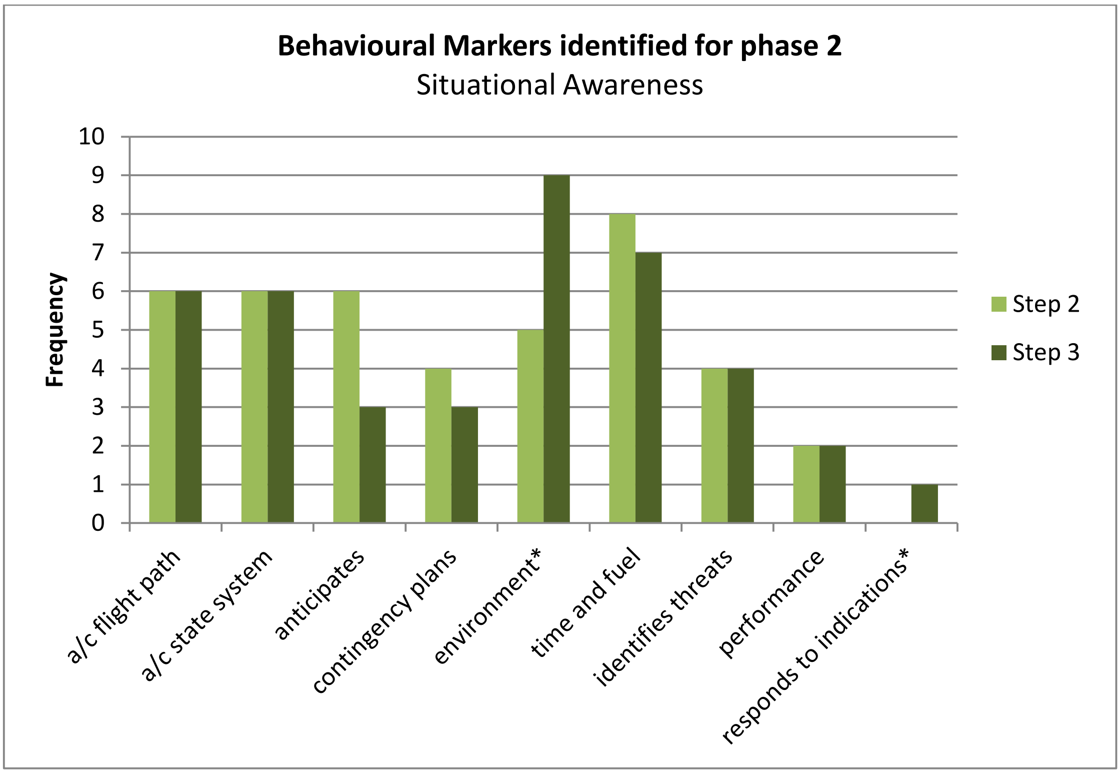


Figure 87: Behavioural Markers concerning Situational Awareness selected for Phase 2 (n=10, * indicates a significant difference between step 2 and step 3 with 95% confidence)

For phase 2, Pearsons calculation only shows a significant correlation between **contingency plans** and the performance rating of SA (*r=.583, p=0.009*), considering both step 2 and step 3.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

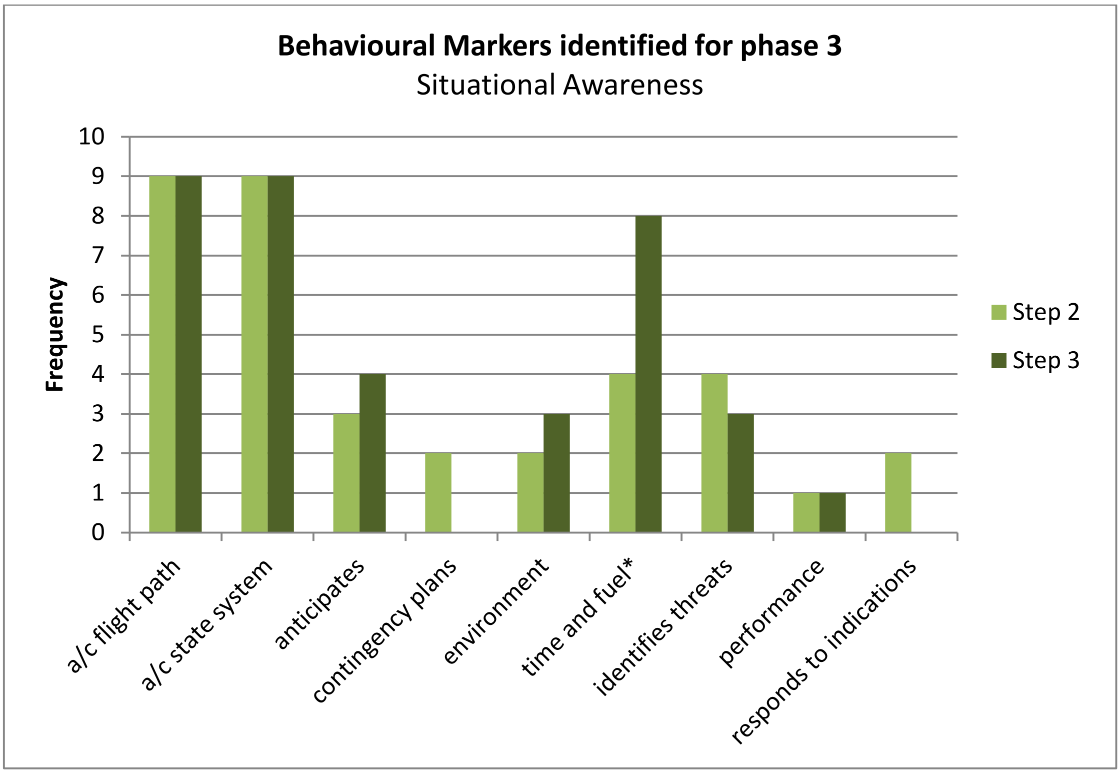


Figure 88: Behavioural Markers concerning Situational Awareness selected for Phase 3 (n=10, * indicates a significant difference between step 2 and step 3 with 95% confidence)

For phase 3, no significant correlations were found between the behavioural markers and the SA performance ratings.

2.12.3. Discussion

No significant differences were found in the performance ratings for Problem Solving and Decision Making nor for situational awareness between the step 2 HMI and the step 3. For phase 3 a trend was found that may suggest that the performance on PS&DM was higher with the step 3 compared to the step 2. This is interesting because phase 3 was also the phase when the situation became most critical and increased the pressure on the pilot monitoring. If the suggested higher performance is due to the HMI changes this would be a good achievement.

Comparing the frequency the behavioural markers were checked for step 2 and step 3 would not be valid if it is not considered if the rating given was positive or negative. Therefore correlations between the ratings and the frequency with which a behavioural markers was checked were determined. If a positive correlation exists the comparison between the frequencies of step 2 and step 3 can be made.

Several positive correlations were found between performance and some behavioural markers, which are phase specific. No negative correlations were found between the performance ratings and the number of times a behavioural marker was ticked. Apparently, the reasons for a negative performance differ and were not catogorised by the same behavioural marker.

In phase 1 searching accurate info positively correlates with PS&DM performance ratings (for step 3) and the frequency the behavioural marker was selected was also significantly higher for step 3. This could be interpreted as a positive result for step 3. In phase 2 we see that the behavioural markers for improvising and searching accurate info correlate with higher performance ratings for PS&DM and also are significantly more often selected for step 3 compared to step 2.

In phase 3, where a trend suggests better PS&DM for step 3 no significant differences are found between the frequencies with which the behavioural markers were selected.

Concerning the reliability of the data, it was mentioned by instructors that the pilot flying (the confederate pilot) was sometimes ahead of the pilot monitoring, which made it difficult to judge the pilot monitoring performance. Also the quality of the video and the fact that several video streams were presented simultaneously made it sometimes difficult to observe everything. The competencies of PS&DM and SA also have some overlap. Comparing the behavioural markers also shows some highly related behaviours between the two competencies, which might also be of influence on how the instructors used the app to make the ratings.

In conclusion, the results suggest an improvement for the pilot monitoring's PS&DM in phase 3, where the new ATIS K with the wind shift is received by the crew up until touchdown. This is the most critical phase. Considering the behavioural markers selected the results may indicate an improvement in the ability to search accurate info with the step 3 compared to the step 1 in phase 1 (Approach) and 2 (AC BUS 1 Fault) and also an improvement in improvising in phase 2.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

2.13. Benefits questionnaire & Performance Curve

The **benefits questionnaire** is an instrument that aims to support the assessment of the impact of the new HMI (Human-Machine Interface) on the pilots' performance as well as to collect feedback on its usability. This was used together with the **HPE Performance Curve**, already used in STEP1, which is a tool that aims to support pilots in self-assessing their own performance during the run.

The **benefits questionnaire** is based on the adaptation of technology acceptance model (Biassoni et al., 2016) and it systematically covers the pilot's attitudes on the new HMI according to the perceived usefulness and ease of use of specific HMI features. More specifically, the purpose of this questionnaire is to enable the understanding of how the interaction with the new HMI can support the pilot's cognitive load and executive functions related to both the monitoring and piloting tasks. It is also intended to collect bottom-up inputs that could serve as a basis for future refinements and evolution of the new cockpit design.

The questionnaire consists of 36 questions investigating the usability of the new HMI, the pilots' willingness to use it in daily operations, and its impact on pilot's cognitive load and executive functions. With the aim to collect both quantitative and qualitative data, the questionnaire was carried out by interview led by two Human Factors (HF) Specialists. The first 29 questions are intended to collect quantitative scores (5-point scale: 1 = Completely agree, 2 = Agree, 3= Neither agree nor disagree, 4 = Disagree, 5 = Completely disagree) but also represent proper topics of discussion aiming to go deeper and fully understand the pilots' point of view and catch their underlying needs and expectations. The last 7 questions are purely qualitative, aiming to summarise what the pilots' liked, disliked and felt missing, as well as collecting ideas for future automation. The full questionnaire is available in Appendix C.

This Section presents the results of both the benefits questionnaire and the HPE Performance Curve. Sub-section 2.13.1 shows the results concerning the usability of the new HMI and the pilots' willingness to use it in daily operations, while Sub-section 2.13.2 illustrates the impacts of the new cockpit design on pilot's cognitive load and executive functions, focusing on workload, attention, situation awareness, problem solving, decision making, execution tasks and team-working. Sub-section 2.13.4 briefly illustrates the results of the benefits questionnaire filled in by the confederate pilots twice, aiming at assessing the perception of STEP2 and STEP3 after repeated use, mitigating the potential novelty effect. Sub-section 2.13.4 presents the results of the HPE Performance Curve. The collected ideas for future automation are summarised in Sub-section 2.13.5. The main findings and considerations are summarised and further discussed in the last Sub-section 2.13.6.

2.13.1. HMI Usability & Willingness to Use

An in-depth usability analysis was performed through the benefits questionnaire, expanding also to other aspects relevant from a Human Factors perspective: perception of reliability, comfort, and willingness to have the new HMI on board the operating A320. This was complemented with pilots' comments and feedbacks on specific aspects, tools and features of the new cockpit design.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

From a purely **usability** perspective, the evaluation of the new HMI is considered positive. Various dimensions were investigated:

- Intuitiveness & Ease of Use – Question n. 3: '*The new interface is intuitive and easy to use*';
- Ease of reading & Interpreting – Question 6: '*The information provided by the system is easy to read*' and Question 7 '*The information provided by the system is easy to interpret*';
- Ease of browsing through flight details information – Question n. 22 '*The touch-screen NAV-Display eases the browsing through flights details information*';
- Usability of touch-screen flaps: Question n. 29 '*The touch-screen flaps are preferable to conventional flap controls*'.

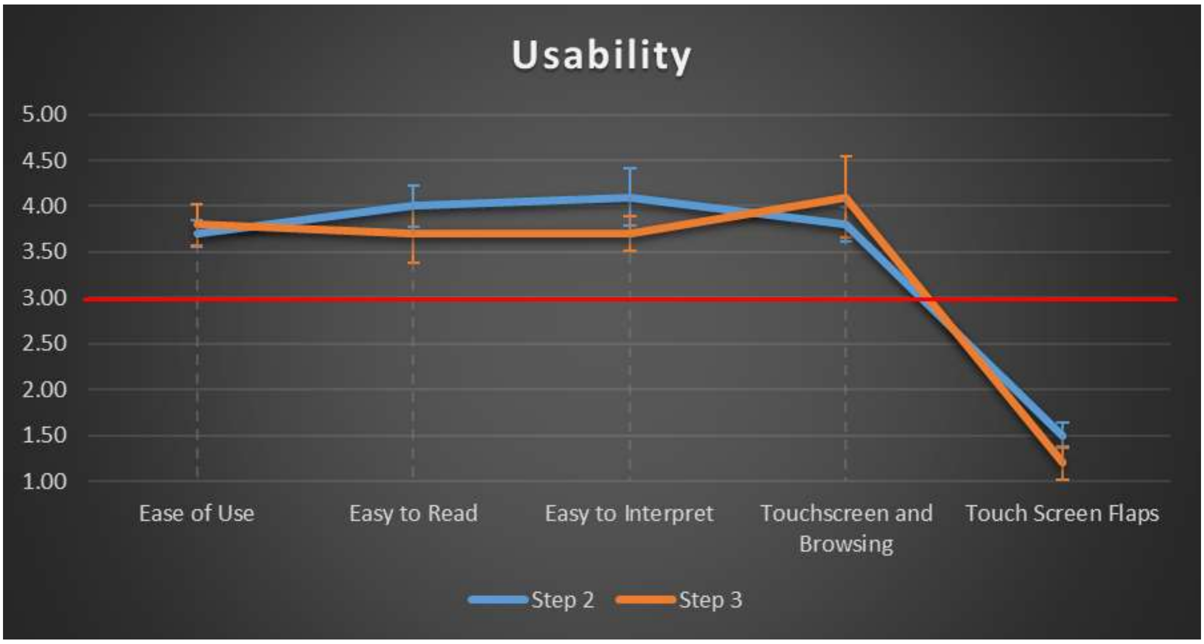


Figure 89: Usability

Figure 89 shows the answers (5-point scale on the vertical axis) of both STEP2 and STEP3 pilots, in blue and orange respectively. Overall, the HMI is considered **pretty intuitive, quite easy to use, read and interpret**. The slightly lower score of STEP3 pilots concerning the ease of reading (6) and interpreting (7) is mostly due to the orange fuel ellipse which concept was not much understood and appreciated: "*Something which is not there (it disappears) is not alarming you*" (STEP3 Pilot).

Furthermore, comparing to the current A320 Cockpit, the **browsing through flight details information seems to be easier** thanks to the new NAV-Display. The explanation could be easily caught in the words of a STEP3 pilot: "*Nokia vs I-Phone*".

However, negative is the view of all the pilots on **the touch-screen flaps**. The main reasons the flaps were disliked are the followings:

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

- Tactile feedback is missing: it is fundamental for pilots to receive a feedback when the flap settings are changed: "*If you are flaps 1 and want flaps 2, with the lever you will feel the notches*" (STEP2 Pilot). Therefore, the system should provide either a tactile or a visual feedback on flap setting changes;
- Foreseen negative impact on safety: the change of flap settings requires to look at the display, target the item and perform the action. This is considered very likely to increase the number of mistakes: "*The touch-screen flaps lever would be a disaster*" (STEP3 Pilot).
- It is time consuming: the change of flaps settings cannot be performed without focusing on this action. Different is with the current lever which allows pilots to perform the action while looking and paying attention to something else: "*You watch on your lever and you can look back and pay attention to another thing. Here you have to target your item and it is more time consuming*" (STEP2 Pilot).

Broadly speaking, besides the flaps lever, there are **various levers and switches that pilots would like to stay mechanical**: thrust lever, speed breaks, gear lever, all guarded/non-reversible switches (e.g. engine fire push button), autopilot on-off button, and communication panel.

The **perception of reliability** of the new system was also investigated, focusing on:

- Accuracy – Question n. 4: '*The new interface presents the information in an accurate way*';
- Promptness – Question n.5 '*The new system provides you with the right information at the right time*'.

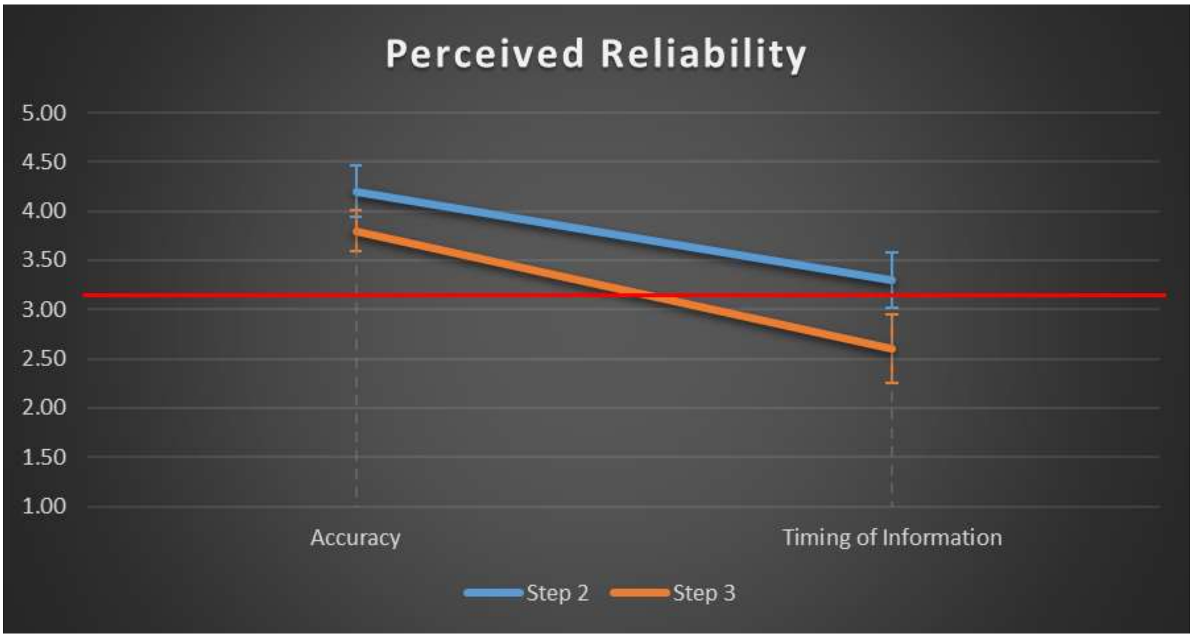


Figure 90: Perceived reliability

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

The new HMI is considered **accurate**, from both STEP2 and STEP3 Pilots. However, as shown in Figure 90, a slightly lower score for STEP3 Pilots is recorded and it is mostly due to the not well-received orange fuel circle above mentioned. The **promptness** of the system, in terms of provision of the right information at the right time, is however a point seemingly critical, especially in the advanced cockpit design tested in STEP3. The score of STEP2 Pilots is still above the threshold, but the following criticalities were remarked:

- Missing information:
  - Speed band for flaps extension,
  - Selected altitude indication on PFD,
  - DME on PFD,
  - Wind information (e.g. cross-wind limitations),
  - Engine power;
- Misleading information:
  - Not fixed distance on NAV Display.

Moving to the STEP3 advanced cockpit design, the score goes below the threshold. Besides remarking the points emerged in STEP2, STEP3 Pilots reported the followings:

- Misleading information:
  - Time remaining: the fuel remaining expressed in time was very much appreciated. However, this information could be misleading in case of situations requiring different fuel consumption such as go-arounds;
- Information available but not automatically displayed: STEP3 Pilots particularly appreciated the idea to be freed from some activities, mostly referring to the search of the landing checklist – which digital version is provided by the new HMI – and the collection of information on RWY status – which is accessible from the new NAV display. However, they would like to have that information automatically displayed: "*The system hides information. I had to actively go to airport-info-and there it says runway 27 is not possible anymore*" … "*It could save time and clicks!*" [STEP3 Pilot].

In general, the type and amount of information provided to pilots should be carefully defined, aiming at avoiding cases of information overload likely to happen in high stress situations: "*It is too much for my small brain!*" (STEP2 Pilot). Adaptive automation solutions could be considered to address this risk.

Comfort and **willingness to use** are other two areas explored:

- Comfort – Question n.1 '*You felt confident using the system, despite its novelty*';
- Willingness to use – Questions n.2 '*You would like to use the new interface in your daily activity*', n. 31 '*Is there any aspect from the new cockpit design that you'd like to see in your own cockpit?*', and n. 32 '*Was there anything you didn't like, or didn't find useful, or felt was missing?*'.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

Figure 91: Comfort & Willingness to use

Despite the novelty of the system, the average score of both STEPs is still above the threshold as shown in Figure 91. The matter of practice was remarked by almost all the pilots: "*The system is good, but we need more time to get used to it*" (STEP2 Pilot). This strongly relates to the intuitiveness and ease of use of the new HMI, which in fact positively correlate ($r = 0.701$, $n = 20$, $p = 0.001$).

Overall, pilots tended to feel confident during normal operations and started feeling uncomfortable when the situation became more challenging: "*It depends from the situation, at the beginning yes, but after the abnormal not at all*" (STEP2 Pilot). Indeed, it is well-known that when the mental demand increases, dealing with a new system becomes harder.

Positive is also the score related to the willingness to use the new HMI ($M= 3.65$; $SD=0.8$), with more than 75 percentiles already reaching a value of 4. This aspect was further explored by asking pilots to mention and comment the tools or features they particularly liked or disliked.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

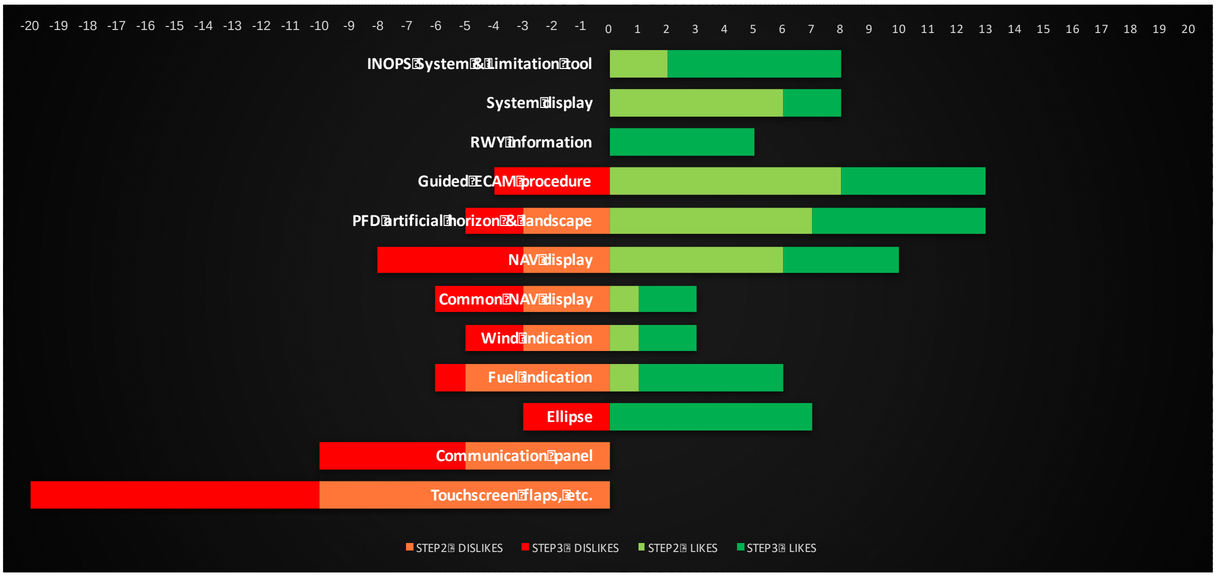


Figure 92: Likes and dislikes

Figure 92 summarises the answers of all 20 pilots, where the lighter colour corresponds to STEP2 pilots while the darker one represents the STEP3 subjects. Each line represents a specific tool/feature. The green bars on the right represent the 'likes', counting the number of pilots who mentioned the specific tool/feature as something they would like to see in their own cockpit. However, the orange/red bars on the left illustrate the 'dislikes', counting the number of pilots who negatively mentioned the specific tool/feature.

The INOPS System & Limitation tools and the System Display counts only 'likes': "*The new version gives you the real picture, you really think you understand what is going on and you always see the limitations, they are there without retrieving the status all the time*" (STEP3 Pilot). The **INOPS System & Limitation tools** were particularly appreciated for its intuitiveness and its capability to raise the situation awareness on the a/c status by providing a better overview. The **System Page** was well-received for the support it provides to the ability to anticipate the future course of events and decision-making, together with its positive impact on workload.

Only 'likes' are counted also for the **RWY status information feature**. It was very well-received, mostly for the support it provides to the ability to anticipate the future course of events, decision-making and for its positive impact on workload: "*You don't have to collect all the information yourself. The computer does it for you!*" (STEP3 Pilot). However, two possible improvements were suggested:

- Provision of information also about 'the why' of the airport status: "*Red and green is not enough. I wanna know why*!" (STEP3 Pilot);
- Automatic display of RWY status information, as already mentioned above.

The **Guided ECAM Procedure** was another tool particularly appreciated by the majority of the pilots. It reduces workload and allows to save time by shortening the execution of procedures. Furthermore, a

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

positive impact on the risk of errors is recognised thanks to the direct switching of the right buttons: "*For me the error is 'doing something you are not supposed to do', like switch something else, in a different direction. The ECAM now is very clear and very structured and you cannot do those types or errors*" (STEP3 Pilot). However, room for improvements and potential criticalities were reported:

- Uncomfortable position: it should be located in pilot sightline (together with the system display). The ECAM in the current position:
  - Leads to risk of distraction: "*The ECAM is positioned below, and it took my attention a little bit*" [STEP2 Pilot],
  - Makes it difficult to monitor: it should be closer to the PFD *"… So that it is easier to monitor the actions the other pilot is doing*" [STEP3 Pilot].
- Possible negative effects on:
  - Pilots' system awareness (short-term effect): "*If you just click-click-click you may miss the complexity and awareness of the situation*" [STEP2 Pilot],
  - Pilots' system knowledge (medium/long-term effect): "*I check the item and then it's done for me, but I don't do it myself. Now I understand less of what's happening… I'd be more like a monkey*" [STEP3 Pilot].
- Does not keep track of what's done: *"… Pilots may do it quickly without actually memorising all the steps. After the procedure is completed, there is no way to check what's on and what's off"* [STEP3 Pilot].
- The distribution of responsibilities is unclear: "*Do I have the possibility to override the system? If I know that I should disregard one point, because we both pilots know is the best flow of actions, I don't know if I just have to do the click, do I have complete control of the system? Who decides? Who has control?*" [STEP2 Pilot].

Particularly appreciated was also the **Artificial horizon on the PFD**. The reasons behind the few 'dislikes' are mostly related to the amount of information displayed which was distracting and to the risk to rely on an artificial horizon. The option to activate/deactivate the artificial horizon was suggested as possible solution.

The **NAV Display** was mostly appreciated for being larger, touch-screen and for its zooming in and out function and vertical profile representation. The majority of the pilots did like the new display but found it distracting and reported difficulties to orientate in certain moments because:

- The distance scale was not fixed and standard: this makes it difficult to get oriented, requiring more attention – "*When you have a standard indication, you don't have to look at the exact numbers… If you miss a standard information like that, you have to think about it*" (STEP3 Pilot) – and increasing the risk of errors – "*I saw too later that we were flying in the wrong direction*" (STEP3 Pilot);
- Too much information displayed;

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

- Unclear flight path symbols: "*The distinction between way-points and airports was not so clear for me*" (STEP3 Pilot). Furthermore, the way-points were confusing because their names and/or numbers was not indicated;
- Unavailability of modes other than NAV Mode (e.g. ARC Mode which is particularly used during the final approach).

Having a **common NAV Display** instead of two was appreciated as it eases the collaboration between pilots: "*It helps to be on the same page!*" (STEP3 Pilot). However, the pilots' need of setting different ranges is of primary importance and needs to be addressed: "*While the PF is maybe interested in planning his approach, the PM would for instance just like to check out the distance to the next diversion airport, but cannot do that immediately because he would have to change the range on the NAV display and disturb thereby the PF. I do like the centralized NAV Display as a working together tool, but I would still like to have at least a small own navigation tool to adjust to my personal style*". The possibility to add an automatic re-set of a standard mode and range after a certain number of seconds, or a saving and retrieving function of the previous settings with a single click are potential solutions to be considered.

Passing to the **fuel indication**, it was mostly disliked in STEP2 because of its too small dimension, while the enhanced indicator tested in STEP3 was particularly appreciated for both the translation in minutes of fuel remaining and the changes in colour (from blue to red) below a certain level. The majority of STEP3 pilots positively judged also the **red fuel ellipse** which was defined useful and helpful. It is considered a powerful supporting feature, capable to help pilots to anticipate the future course of events – "*It is easy to plan ahead, because of the circle of the fuel and the information about the airport…*" (STEP3 Pilot) – and to reduce the risk of tunnel attention in abnormal situations: "*If you get focused on repairing a failure, and you have the circle closing in, it catches your attention, and so it may help you to get out of this tunnel*" (STEP3 Pilot). Different was the judgment of the **orange fuel ellipse** which concept, as previously mentioned, was probably not fully understood, thus not well-received.

Only 'dislikes' are counted for both the already discussed **touch-screen flaps** and the **communication panel**. The latter was considered more difficult to use and less intuitive in comparison to the traditional radio management panel. Furthermore, questions and concerns on its usage in case of high turbulences or abnormal situations, such as smoke in the cabin, were raised.

2.13.2. Impact on pilot's cognitive load and executive functions

The analysis of the "likes and dislikes" can be rated to the impact of the tools on the HPE factors. In fact, HMI device-specific features can affect Usability, Perceived Ease of Use and can determine the perceived impact of the HMI on HPE factors, modifying pilot's attitude after use and their Willingness to Use of the HMI. At the same time, the pilot's perception of the variation in the HPE factors can affect the Perceived Usability and Ease of Use, since high impact on perceived Workload, Attention, and Situation Awareness could affect not only the performance, but also their feelings on the HMI.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

If high workload, low situation awareness and high values of stress are experienced, it could be hypothesised that the Perceived Usability and Ease of use should lead towards lower scores, undermining acceptance after use. At the same time, if low workload, high situation awareness and low values of stress are experienced, it could be hypothesised that the perceived usability and ease of use should lead towards higher scores, encouraging acceptance after use (Figure 93). Thus, measuring the way the HMI is evaluated after use in Step 2 and Step 3 can provide good insight on the process that generated the pilot's judgement and performance.

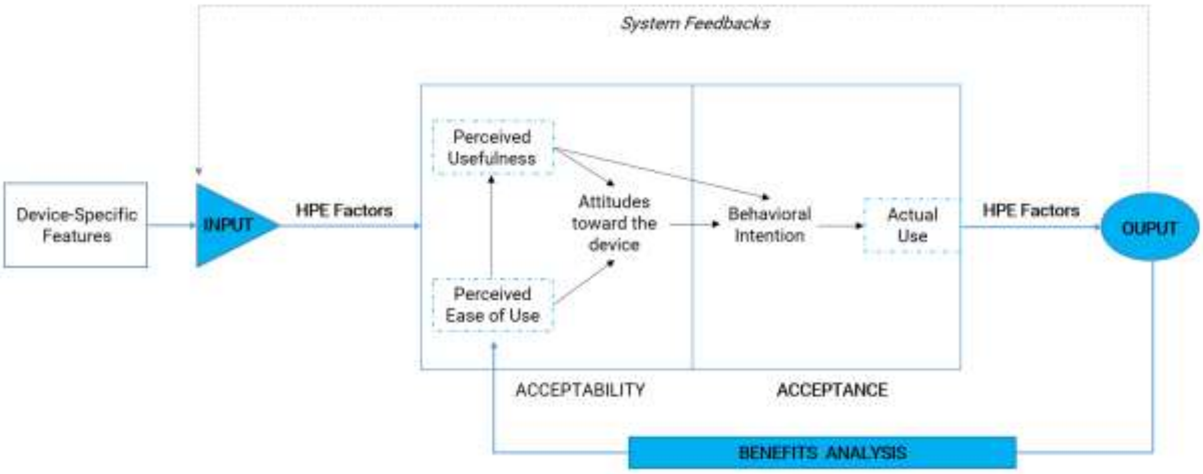


Figure 93: HPE Factors and Benefits Analysis Model adapted from Technology Acceptance Model

In this section the overall and singular perceived impact of the HMI on the HPE factors is analysed. The specific impact of the system on these factors is also discussed. Considering all the items in the benefits questionnaire and the small sample size, it was possible to start just an initial exploration of the variance in the pilot's response. A potential indication to reduce to five main factors emerged, as able to describe with almost 64% of the total variance the perceived impact on the HPE factors (Figure 94).

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

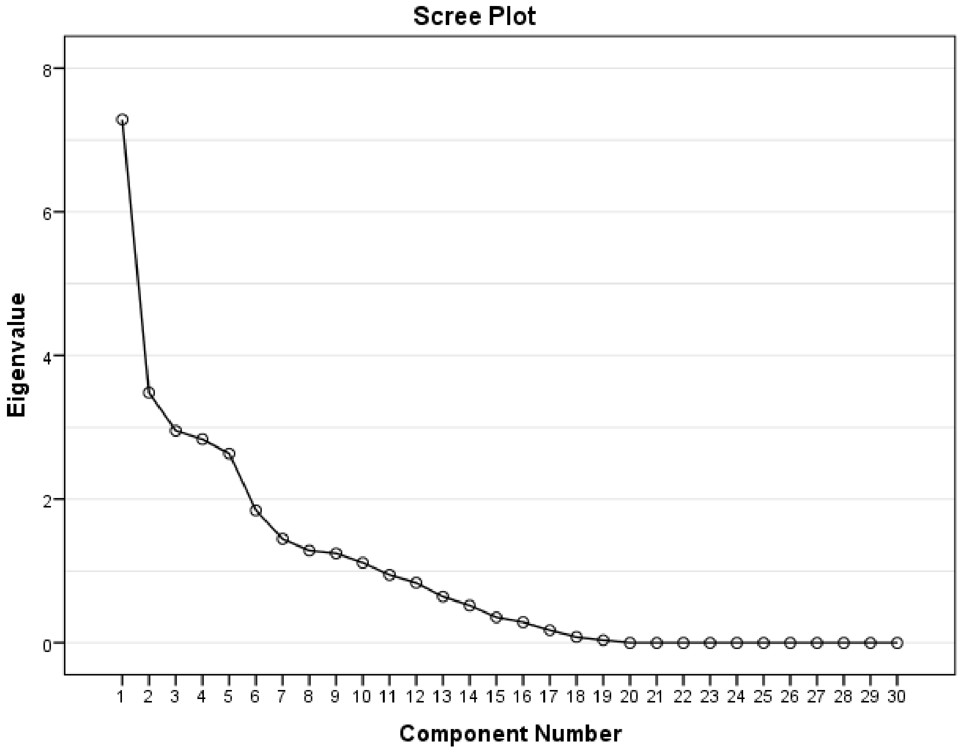


Figure 94: Total Variance Explained by the Benefits Analysis

One factor was saturated by the items that refer mainly to **Workload**:

- Question n. 10: '*The new interface is likely to reduce pilots' workload in* ***normal situations***' – Loading for .728;
- Question n. 11: '*The new interface is likely to reduce pilots' workload* ***in unexpected/abnormal situations***' – Loading for .624.

A second factor was statured by items relating to **Situation Awareness**;

- Question n. 20: '*The new interface is likely to raise and keep high your* ***awareness on fuel***' – Loading for .816;
- Question n. 28: *The failure tree indication improves the situation awareness of aircraft* ***system failures***" – Loading for .649;
- Question n. 19: '*The* ***artificial landscape*** *provided by the primary flight display is likely to improve your situation awareness*' – Loading for .617;
- Question n. 21: '*The* ***use of colours*** *is likely to promptly direct your attention towards the most relevant information'* – Loading for .534.

A third factor was saturated by items relating mainly to **Attention**:

- Question n. 12: '*The new interface is likely to reduce the* ***risk of distraction***" – Loading .654;

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

- Question n. 13: '*The new interface is likely to reduce the risk of* ***tunnel attention***' – Loading for .599.

The fourth factor was saturated by items regarding the **Perceived Usefulness in Problem Solving and Decision Making**:

- Question n. 30: '*The interface is likely to better support the selection of* ***alternate airports*** *in* ***low fuel situations***' – Loading for .756;
- Question n. 25: '*The* ***abnormal procedure checklist*** *is likely to improve the safety of operations by minimizing the likelihood of errors*" – Loading for .626;
- Question n. 15: '*The new interface is likely to better support complex problem solving and* ***decision-making processes***' – Loading for .506;
- Question n. 17: '*The pilots' ability to* ***anticipate or predict the future course of events*** *is likely to be better supported by the new system*' – Loading for .507.

The final factor was related to Perceived Ease of Use of **Task Execution**:

- Question n. 8: '*The new interface is likely to effectively support the* ***monitoring task***' – Loading for .923
- Question n. 9: '*The new interface is likely to effectively support the* ***piloting task***' – Loading for .637;
- Question n. 24: '*The abnormal procedure checklist is likely to* ***shorten the execution of ECAM procedures***' – Loading for .787;
- Question n. 18: '*The way the information is presented in new interface is likely to ease the* ***collaboration between pilots***' – Loading the factor for .618;
- Question n. 26: '*While using the abnormal procedure checklist, the indication of the number of overflow items is an information likely to help in* ***time management***' – Loading for .547.

Perceived Impact on Workload

Repeated-Measure ANOVA for perceived Workload (in Expected situation; in Unexpected situations) x Step (Step2; Step3) was performed to identify potential differences in the way the new HMI supported Pilots' Workload in both steps. Overall, as show in Figure 95, the HMI was considered capable to positively impact Workload, especially in unexpected/abnormal situations (M=4.0; SD=0.8): "*It is better especially in abnormal situations: for example, I like the presentation of INOPS system and resulting limitations*" [STEP3 Pilot]; "*Everyone is seeing what is doing, you see what you have done... You have feedback, the image is there, is something that helps during unexpected/abnormal situations*" [STEP3 Pilot]; "*The fuel-indication circles, the system-display, the ECAM, the view of limitation, the information of runway not available… That helps reducing workload in unexpected situations*" [Step3 Pilot].

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

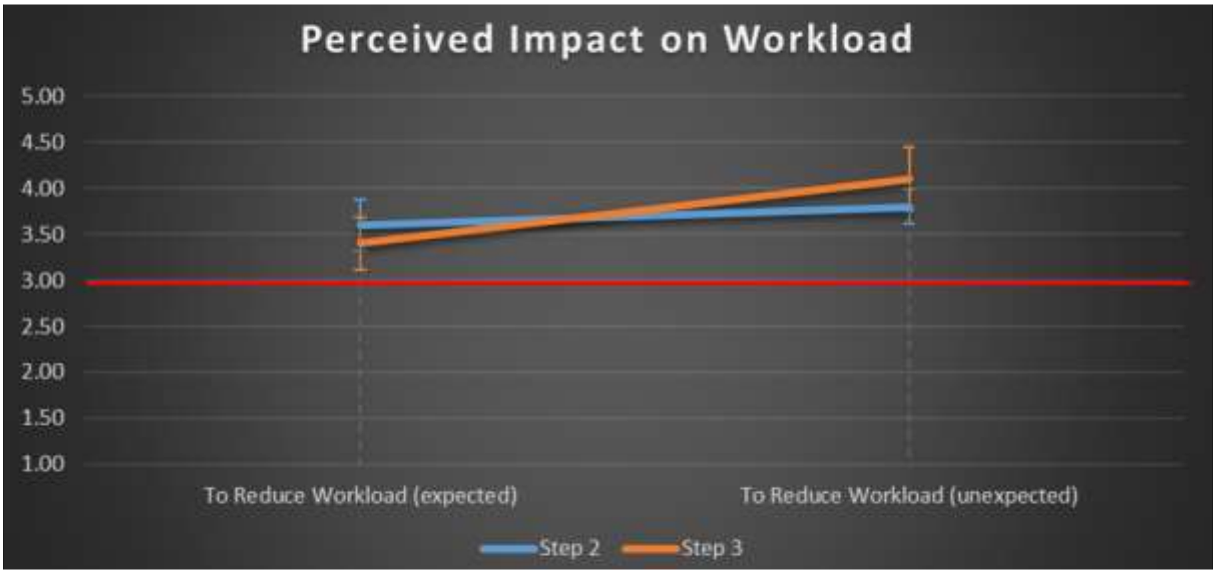


Figure 95: Perceived impact of the HMI on Workload

No significant differences were found among Step 2 and Step 3: $F(1,20)=1.271$, $p=.274$, $\eta_p^2= .066$.

Perceived Impact on Situation Awareness

Repeated-Measure ANOVA for perceived impact of different elements of the HMI on Situation Awareness (Artificial Landscape; Fuel Awareness; Colour Coding; Failure Tree indications) x Step (Step2; Step3) was performed to identify potential differences in the way the HMI supported Pilots' situation awareness.

As shown in Figure 96, the HMI was considered to have an overall positive effect on Pilot's Situation Awareness, mostly related to the contribution provided by the Artificial Landscape - *"With the landscape you can see the terrain, the height of the mountain, your position. I think it is the best improvement"* [STEP2 Pilot] – and the Failure Tree indications.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

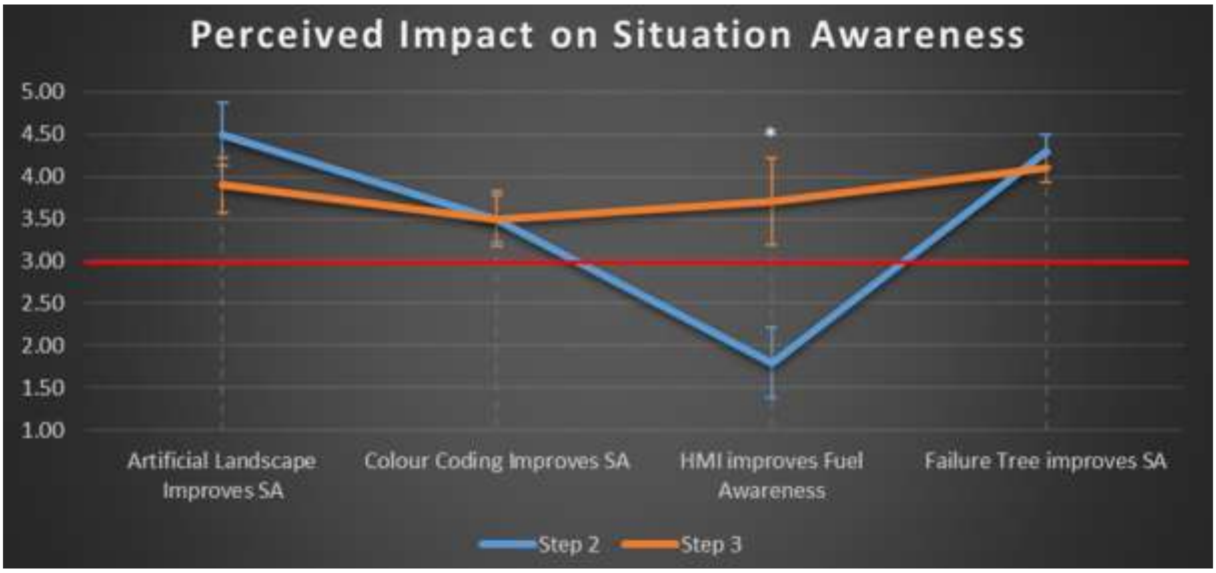


Figure 96: Perceived impact of the new HMI on Situation awareness, for Step2 and Step3

Furthermore, it is observed a statistical difference in the overall perceived impact on Situation Awareness $F(3,20)=5.610$, $p=.002$, $\eta_p^2= .238$. In particular, the post hoc analysis revealed an additional significant relevant difference on the perceived impact of the HMI on Fuel Awareness $F(1,20)=9.101$, $p=.007$, $\eta_p^2= .336$:

- STEP2 Pilots considered the new interface not as effective for promoting fuel awareness (M=1.8; SD=0.8), even compared to the regular A320 interface (M3): *"Small, out of position, and no colour indication when you are in the limit low on fuel and emergency… It is better now in the A320 cockpit"* [STEP2 Pilot];
- STEP3 Pilots, instead, considered the new HMI significantly more likely to increase their Fuel Awareness (M=3.7; SD=0.9): *"With a different training and with some modification, I'd like to see the fuel-ring idea in my own cockpit"* [STEP3 Pilot].

Perceived Impact on Attention

Repeated-Measure ANOVA for perceived impact on Attention (Distraction; Tunnel Attention) x Step (Step2; Step3) was performed to identify potential differences in the way the HMI supported pilots' attention.

Overall, it is observed a neutral assessment on the impact on both Distraction (M=2.9; SD=0.7) and on Tunnel Attention (M=3.5; SD=0.7): *"…if you want to fight the aircraft, it is probably distracting at first. But if you like to have more information regarding navigation, weather, airports, and surrounding, it is helpful..."* (STEP3 Pilot).

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

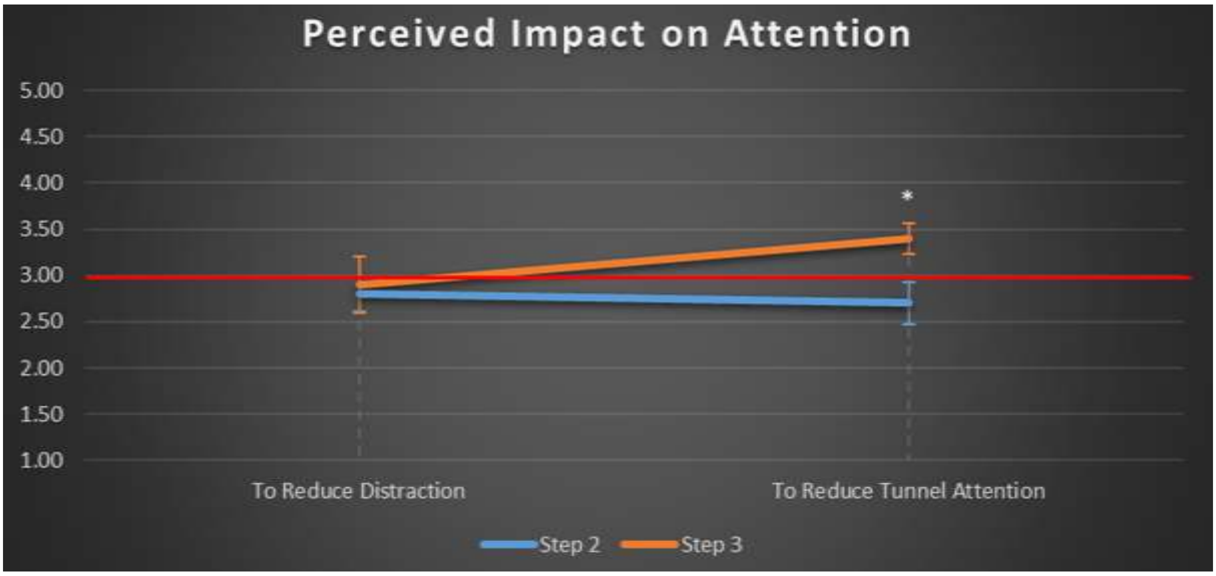


Figure 97: Perceived Impact on Pilot's Attention for Step2 and Step3

However, Figure 97 also shows a significant difference between Step 2 and Step 3 on the perceived impact of the HMI on Tunnel Attention $F(1,20)=6.785$, $p=.018$, $\eta_p^2= .274$. In fact, Step 3 Pilots considered the enhanced HMI as more likely to reduce tunnel attention (M=3.4; SD=0.7) compared to Step 2 Pilots (M=2.7; SD=0.4):

- Step 2: "*It is always in the back of pilot's mind to do checklists. But since now there are so many possibilities to show things... Why don't we structure something to avoid tunnel attention? Like today: the issue was the fuel, and if you concentrate on that, only you could go into a tunnel. Why did the interface not help me in that?*" [STEP2 Pilot];
- Step 3: "*It reduces tunnel attention because, for instance, it showed me clearly that runway 27 was not available, so it made me think about it: 'Why not?' I had to work and get out of the tunnel*" [STEP3 Pilot].

Perceived Usefulness for Problem Solving

Repeated-Measure ANOVA for perceived usefulness for Problem Solving (Likelihood of Errors, Decision Making Stay Ahead of the Plane, Selection of alternate airports) x Step (Step2; Step3) was performed to identify potential differences in the way the HMI supported Pilots' Problem-Solving process. Overall, as shown in Figure 98, the HMI was capable to better support Pilot's ability in some specific problem-solving situations (M=3.8; SD=.76).

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

Figure 98: Pilots' perceived usefulness for specific problem-solving situations

In particular, the new HMI, compared to the baseline A320 (M=3), was perceived positively and useful for decisions on alternate airports to go in low fuel situation, especially for Step3 Pilots (M=4.3; SD =.67): *"In the planning phase it will help for deciding alternate airport"* (STEP3 Pilot).

Perceived Ease of Use in Task Execution

Repeated-Measure ANOVA for Perceived Ease of Use in Task Execution (Monitoring Task, Piloting Task, Joint actions, ECAM Procedure, Time management) x Step (Step2, Step3) was performed to identify potential differences in the way the HMI facilitated the execution of tasks.

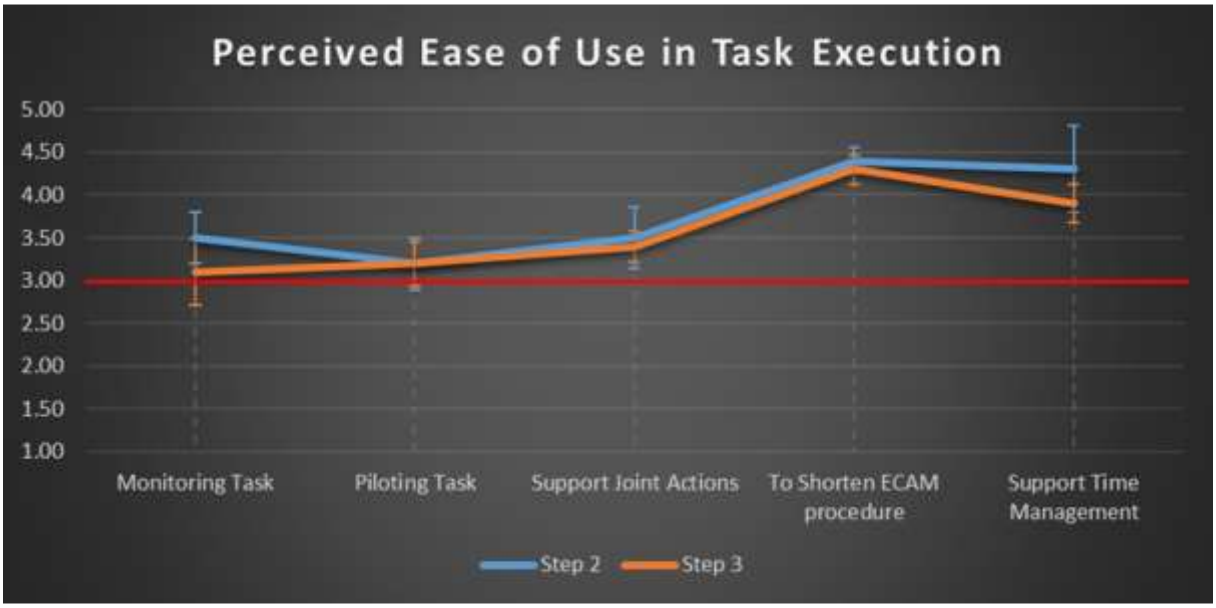


Figure 99: Perceived impact of the HMI on Problem Solving and Task Execution

Overall, as shown in Figure 99, a potential positive impact on task execution was reported by pilots of both Step2 (M=3.8; SD=0.7) and Step3 (M=3.6; SD=0.9). The HMI was perceived better than the current A320 interface (M=3) in supporting task execution, especially for the ECAM Procedure (M=4.35, SD=0.4), while for the general monitoring and piloting tasks no particular improvement compared to the A320 interface were perceived. The values close to the baseline A320 (Monitoring Task, Piloting Task and Joint actions/Teamwork) are mostly related to the already mentioned missing information (selected altitude on PFD, speed-bands for flap extensions, etc.).

Furthermore, the HMI was considered capable to reduce the likelihood of errors related to task-execution.

No significant differences were found among step 2 and step 3 on the perceived impact of the HMI on perceived task execution $F(4,20)=.298$, $p=.878$, $\eta_p^2= .016$.

2.13.3. The Effect of Multiple Use of the HMI

In order to control for the effect of novelty of the HMI, the confederate pilot, who repeatedly used the HMI for one week in STEP2 and one week in STEP3, was asked to fill in the same benefits questionnaire. The aim was to assess the perception of STEP2 and STEP3 after repeated use, mitigating the potential novelty effect reported by the majority of the pilots.

The experienced pilot felt that the HMI is capable to positively support pilots, with the exception of the touchscreen flaps (see Figure 100). It is noticed that a week more of practice allows the confederate pilot to be more confident using the system which was also considered easier to use and more supportive in comparison to STEP2. In fact, a tendency to consider STEP3 better than STEP2 is observed not only for reducing tunnel attention and improving fuel awareness, but also for a series of different aspects.

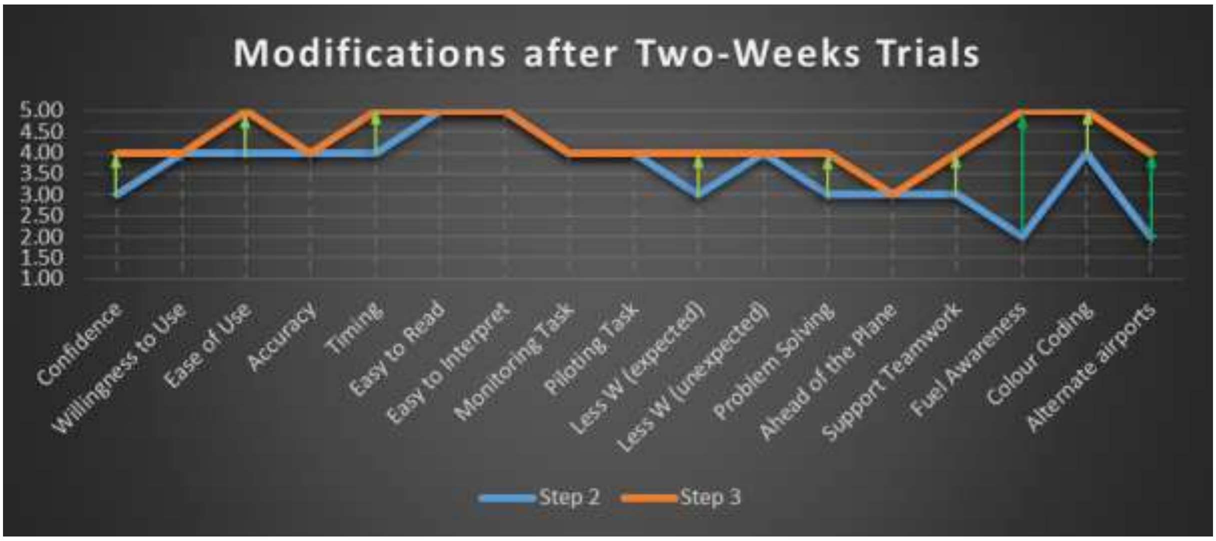


Figure 100: Rating of the interface in Step 2 and Step 3 after one week use of the HMI

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

In particular:

- The promptness of the system was better evaluated,
- The system was perceived more capable to reduce workload in normal situations,
- The confederate pilot felt more supported in solving problems and making decisions,
- The system was perceived more capable to ease the collaboration with the other pilot,
- The awareness on fuel awareness was definitely higher,
- The confederate pilot felt much more supported in the selection of alternates.

2.13.4. HPE Performance Curves

The HPE Performance Curve was used to support pilots in self-assessing their own performance during the run. Each pilot was asked to position him/herself on the curve in three specific moments: the start, the most demanding moment/s, and the end.

Figure 101 and Figure 102 provide an overview on the HPE curves of STEP2 and STEP3 Pilots, respectively, while Figure 103 shows the most demanding moments of both STEP2 and STEP3 pilots on the timeline.

It is observed that all ten STEP2 Pilots were relaxed at the start (Figure 101). Furthermore, all of them reached the highest level of load towards the end of the scenario. In particular, four Pilots reached their peak when making the decision on the airport to go (Pilots n. 21, 26, 27, 28). For other four pilots the worst moment corresponded to the decision on the RWY to land (Pilots n. 22, 24, 25 and 30), one of which kept struggling until the end (Pilot 24). The remaining two Pilots n. 23 and 29 reached their peak only in the last minutes of the run when the final approach started (Pilot 23) and the control was transferred (Pilot 29).

Differently from STEP2 Pilots, most of the STEP3 subjects did not start completely relaxed but already focused and all of them struggled at some point (Figure 102). The first approach with the go-around was the worst moment for Pilots n.33 and 39. The decision-making on the airport to go was the hardest moment for Pilot n.37 but also for Pilot n. 34 who struggled also during the final approach when the control of the a/c was transferred to him. The transfer of control was the hardest moment also for Pilots n. 32 and 35. Three Pilots (n. 31, 36 and 38) reached their peak when realised that there was only one bad option for landing (RWY09). Pilot 40 tended to struggle any time encountered an undesired event.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

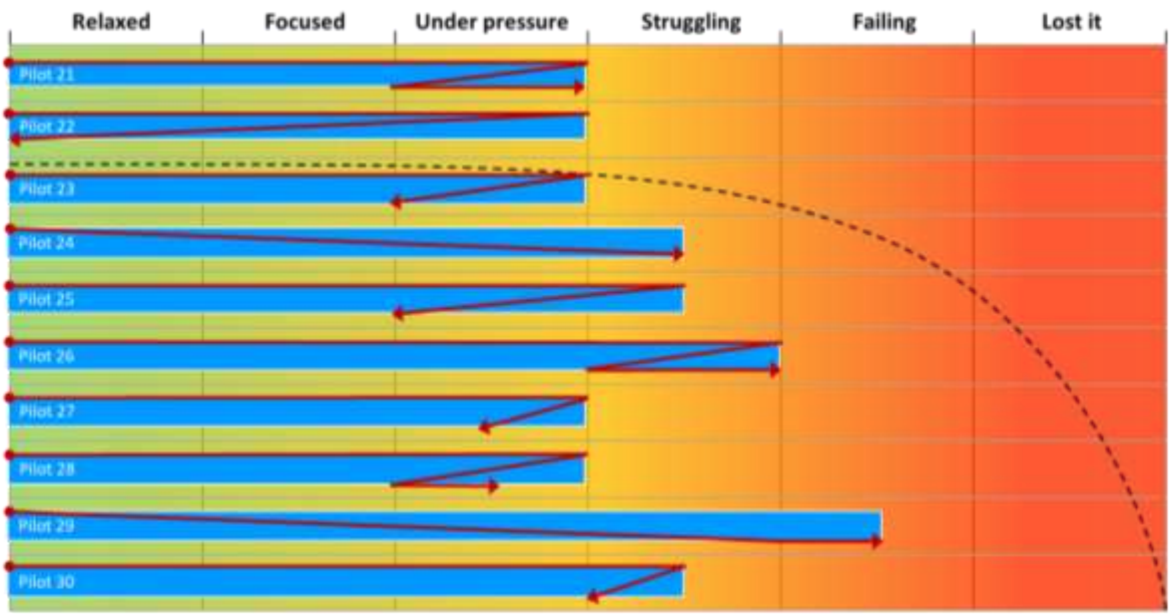


Figure 101: Overview on HPE Curves of STEP2 Pilots

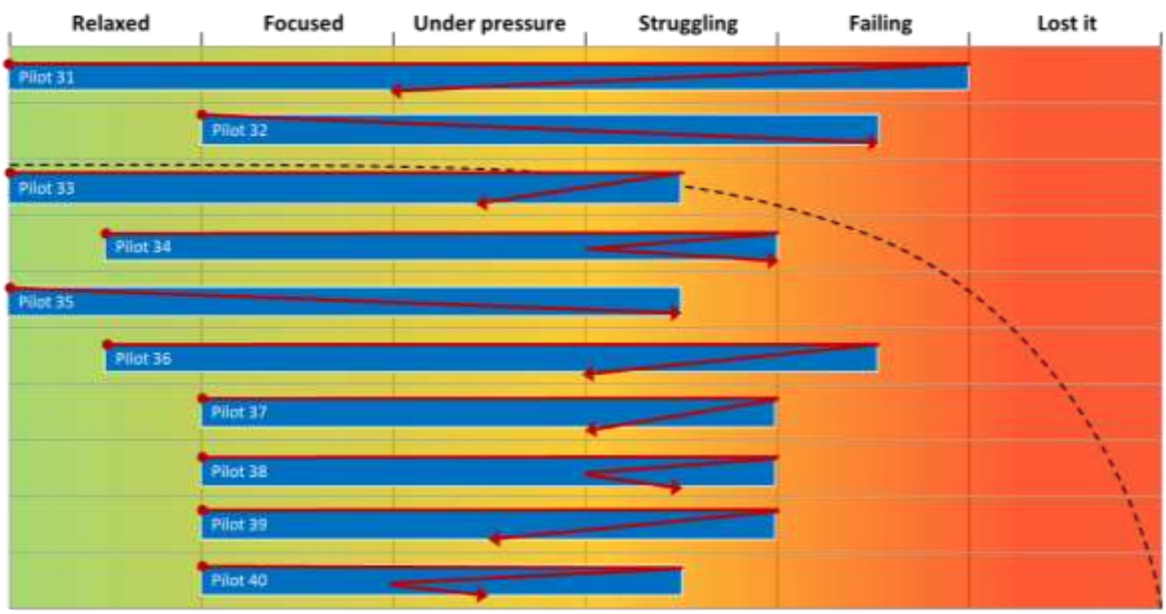


Figure 102: Overview on HPE Curves of STEP3 Pilots

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

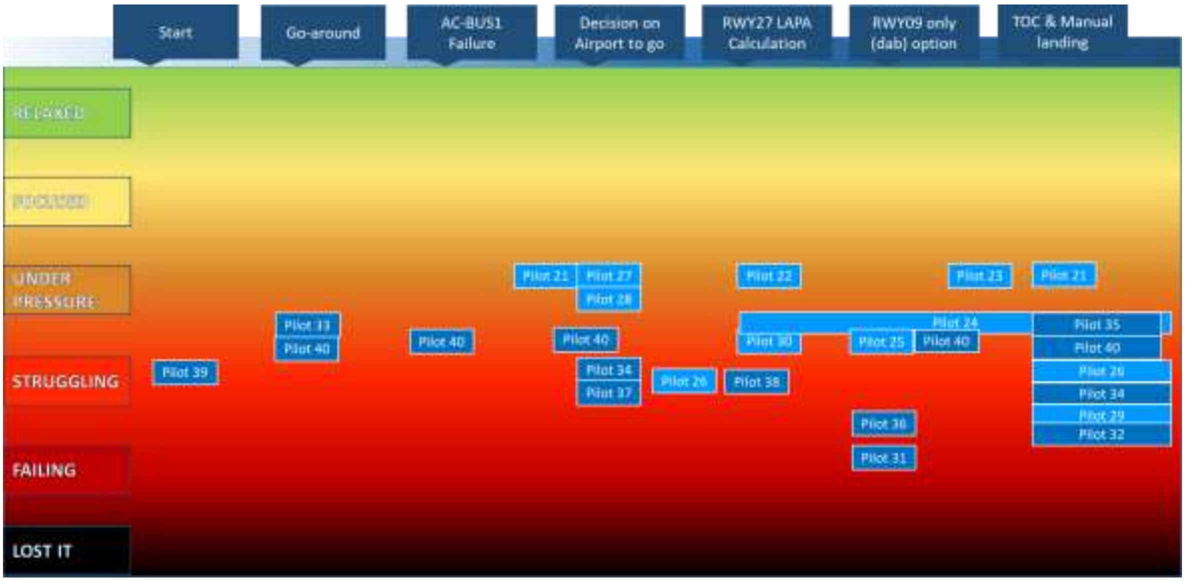


Figure 103: STEP2 and STEP3 HPE Curve peaks & Scenario events

2.13.5.Automation for the future

All the twenty pilots were invited to express their opinions on the design direction taken as well as to suggest any idea for future automation:

- Question n. 35: '*Do you think this advanced design is moving in a good direction?*';
- Question n. 33: '*Do you think this advanced design is moving in a good direction?*' & Question n. 37: '*When your workload is high and you are running out of time, is there something else that you would like the automation to do for you?*'.

The majority of the pilots (8 of STEP2 and 8 of STEP3) were rather enthusiastic and think that this design, with some improvements and refinements, could be the future: "*Yes, it could be the future. Touch screen was very comfortable, but few switches should still stay conventional… When you are stressed is maybe easier to operate a switch!*" [STEP2 Pilot]; "*I would say yes, but I want my thrust lever!*" [STEP2 Pilot]. One STEP2 Pilots answered "*Yes and no*" because he felt overloaded by information: "*It needs to be focused on the important things. Not all the information should be on the screen*". The remaining three pilots (1 of STEP2 e 2 of STEP3) found difficult to answer this question without practicing it properly.

Various ideas for future automation arose, which could be grouped into three categories:

- **Information management:**
  - Remaining air time [STEP2 Pilot] – *Covered in STEP3*;
  - EFP & LAPA integration [various Pilots from both STEP2 & STEP3];
  - Cross-wind computation [STEP3 Pilot];
  - Automatic weather info on NAV display (last update) [various Pilots from both STEP2 & STEP3];

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

- **Communication:**
    - Selection of new frequencies: automatic/by voice, by proposing options to be accepted [STEP2 Pilot];
    - Automatic display of RWY status on NAV display [STEP3 Pilot].
- **Aircraft handling:**
    - Automatic flaps [various Pilots from both STEP2 & STEP3];
    - Automatic gear [STEP2 Pilot];
    - Automatic landing lights [STEP3 Pilot];
    - Automatic landing distance calculation [STEP3 Pilot].

2.13.6. Discussion

Understanding pilots' perceived benefits after the experimental sessions, enabled to collect subjective data on the way the HPE factors affected the performance, based on the pilots' self-assessed performance and points of view. The HMI device-specific features affected perceived usability and pilot's attitude after use of the HMI and, at the same time, the HMI affected the pilot's perception in the two different steps of the variation in the HPE factors

Considering the overall results, no negative effects on workload, situation awareness and stress were perceived by the pilots after the use of the interface. Positive effects, on the other hand, were perceived for: reduction of workload in unexpected situations; improvement of situation awareness (e.g. artificial landscape); perceived usefulness for problem-solving (e.g. alternate airports, stay ahead of the plane); and in easing task execution (e.g. ECAM procedure).

In addition, when considering the improvements in the HMI at Step 3, also positive effects were perceived in Fuel awareness and improvement of attention in critical situation, all elements very relevant for safety operations. The results of the Performance Curve seem to confirm that an increase in the alertness state right from the beginning of the session in Step 3 compared to Step2, can be potentially related to an increased in the focus of attention, caused by the specific changes in the HMI, but additional parameters, like physiological measures, could better investigate the relationship between these dimensions.

Considering all the results together, the benefits questionnaire analysis suggests that the Perceived Usability and Ease of use could lead towards a positive acceptance after use of the new HMI, and they could possibly improve also pilot's performance and executive functions, by easing the HPE factors to stay within the acceptability zone.

The effect of multiple use of the HMI showed that these positive effects may increase over time, with repeated use of the interface increasing the positive scores in the perception of the impact on HPE factors in Step3. This positive impact was present even for some factors that were not manipulated differently in Step3 compared to Step2, suggesting the potential pervasiveness of the HMR factors on the pilot's perception.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

To sum up the main results coming from the analysis of the acceptability and acceptance of the pilots, it can be stated that:

1. The **overall evaluation of the HMI was positive**, with a significant improvement in fuel awareness from Step2 to Step 3;
2. Pilots reported a positive **perceived impact on both workload, situation awareness and decision-making in unexpected/abnormal situations**;
3. The **Touch Screen interface was appreciated** and, in general, it was correlated with perceived benefits, but it presented **still some concerns for safety** to be further investigated and addressed;
4. Finally, for some specific tasks (e.g. extension of flaps) a strong tendency to be **more in favour of full-automation solutions rather than the actual partial automation** was strongly perceived and should be further investigated.

2.14. Cognitive walkthrough

2.14.1. Results

Our results are based on data collected during Step 1 in Braunschweig (A320) and Step 2&3 in Bordeaux (AV2020). For each of the 30 pilots, audio and video recordings of the cockpit and of the control room were made (1 hour each). An hour of cognitive walk-through as well as a trace of events were also produced and analysed. During Step 2&3, the different interfaces were recorded. This data represents 3 hours of recording per pilot for a total of 60 hours of video.

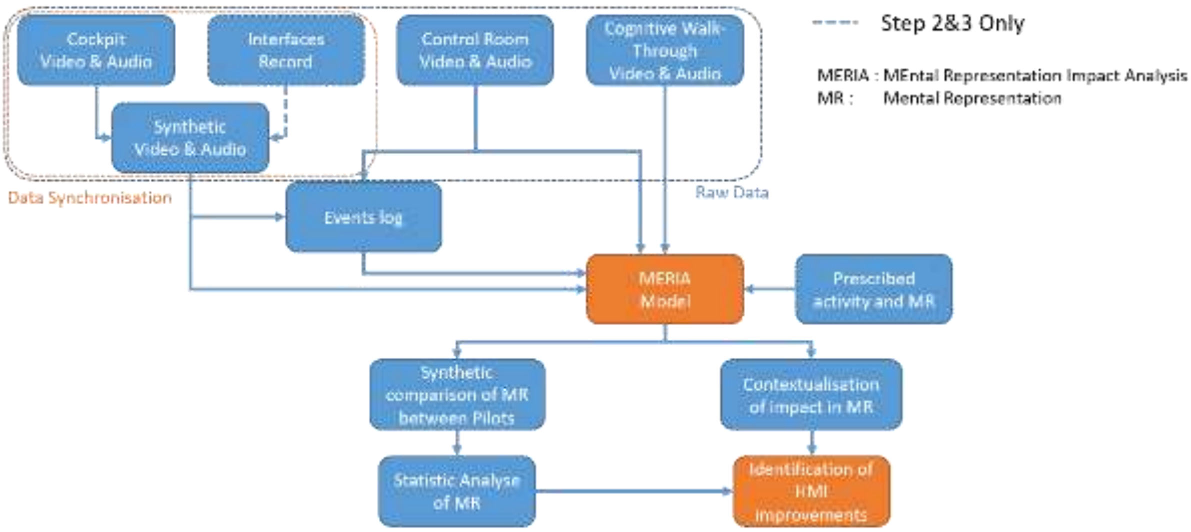


Figure 104: Process Analysis

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

The data were analysed according to the process described in Figure 104. The cockpit videos and interfaces were synchronized in a file called "Synthetic Video & Audio" and transferred to the partner for data analysis. The MERIA (Mental Representation Impact Analysis) data formalization model is built from video data, Events Log), the Cognitive Walk-Through and the expected mental representation

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

Temps	ATC Com	ATC HDG	ATC FL	PNF	PF	Failure	Fuel Kg	Fuel Time	Use of circle	Check RWY Available	LAPA RWY	ATIS
0:51:30	FL 240 HDG 015	015	240				2088					
				ATIS K.								K.
					"That's the next weather"							
0:50:50				ATIS J.								J.
0:50:00	FL 170		170									
0:49:00				LAPA RWY27 wet							27	
0:46:50					Speaks about 300m extra RWY							
0:45:30	HDG 015 FL 090	015	090									
0:44:00							2000					
0:43:40					"Same wind as on the ground"							
0:42:00				"We've 2T of fuel left, in case of missed approach we stay in BRE I guess"								
0:42:00				No diversion possible								
0:41:20	FL 060 HDG 010	010	060									
					Ask for Vapp							
0:40:00	FL 030 HDG 360	360										
					Zoom out sur le ND, cercle orange visible							
0:37:00	HDG 330	330										
0:36:00	HDG 290	290										
0:36:00	Cleared ILS contact tower											
0:35:40	Friction car measuring											
				"ROGBO 6NM" (cercle plus visible)								
					"3000ft in case of GA"							
0:33:00	Cleared to land, friction car measuring in progress											
					"Check wind again"							
0:32:20				Gear down, Flaps 3								
0:32:00				Flaps full								
0:32:00				Landing Briefing Checklist	Landing Briefing Checklist							
0:31:30	GA											
0:31:00				GA	GA		1739	44				
					"We've 3000ft"							
0:29:33	HDG 100	100										
0:29:13	FL 040		040									
0:29:00						ON						
				"So, we climb to 4000ft and then we check for the AC BUS 1 fault"								
0:28:30				Check FL 040								
0:28:10				ECAM actions	ECAM actions							
					"AutoPilot is OFF"							
				Il prend pas le sidestick tout de suite								
0:27:49							1500	39				
					"I've control"							
0:26:30					Asks limitations to PNF							
0:26:10	HDG 090	090										
0:25:30				Understand window heat failure (Right only)								
				"We need an airport with CAT 2 app and not a lot crosswind"								
					"BRE look pretty good"							
0:25:00					Asks OMB							
0:23:30				New app to BRE								
0:23:10	ATIS K.											K.
0:22:20				"Stronger crosswind"								

Figure 105: Extract from an event analysis "Events Log" file

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

The coding process of items through the MERIA model is described in Figure 106.

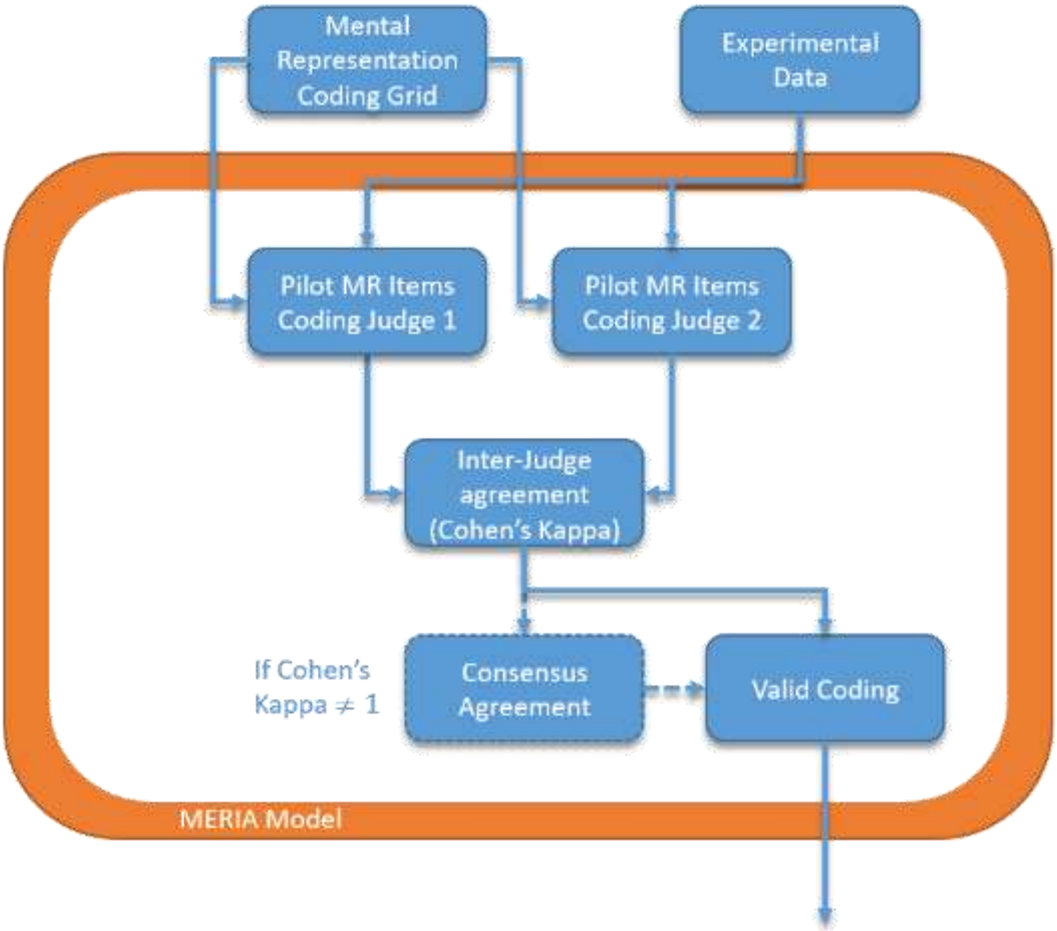


Figure 106: MERIA Process

The data are analysed and classified according to a grid defined by human factor specialist and aeronautical experts. Two judges used the same grid to rate the different pilots. The agreement between the judges is evaluated by Cohen's Kappa method (Cohen, 1960), that is used to determine the probability of agreement between two judges relatively to the probability of a random agreement. We chose to take a quadratic weighting of the inter-judge differences that does not penalize a small coding gap, but amplifies the major gaps. With this calculation of the inter-judge accord, a categorization gap of one category between two judges is penalized 1^2 and, a gap of i categories is penalized i^2. The weight of the error is:

$$w_i = \frac{i^2}{(k-1)^2}$$

k is the number of categories (here k=4).

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

The value of Cohen's Kappa obtained by the calculation represents the agreement between the judges.

k	Interpretation
< 0	Poor
$0.0 - 0.20$	Slight
$0.21 - 0.40$	Fair
$0.41 - 0.60$	Moderate
$0.61 - 0.80$	Substantial
$0.81 - 1.00$	Almost perfect

With this methodology the value of Cohen's Kappa, obtained in quadratic weighting, is **0.8301**. A non-identical coding between judges has been modified to have only one MERIA model per pilot.

MERIA model and analysis

This difference between the judges was resolved by consensual agreement. For each pilot we obtain a MERIA model (Appendix A) similar to Figure 107. Below in Figure 107 we have described an example of how each mental representation item is analysed with MERIA model.

For each pilot we obtain a MERIA model (Appendix A) similar to Figure 107.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

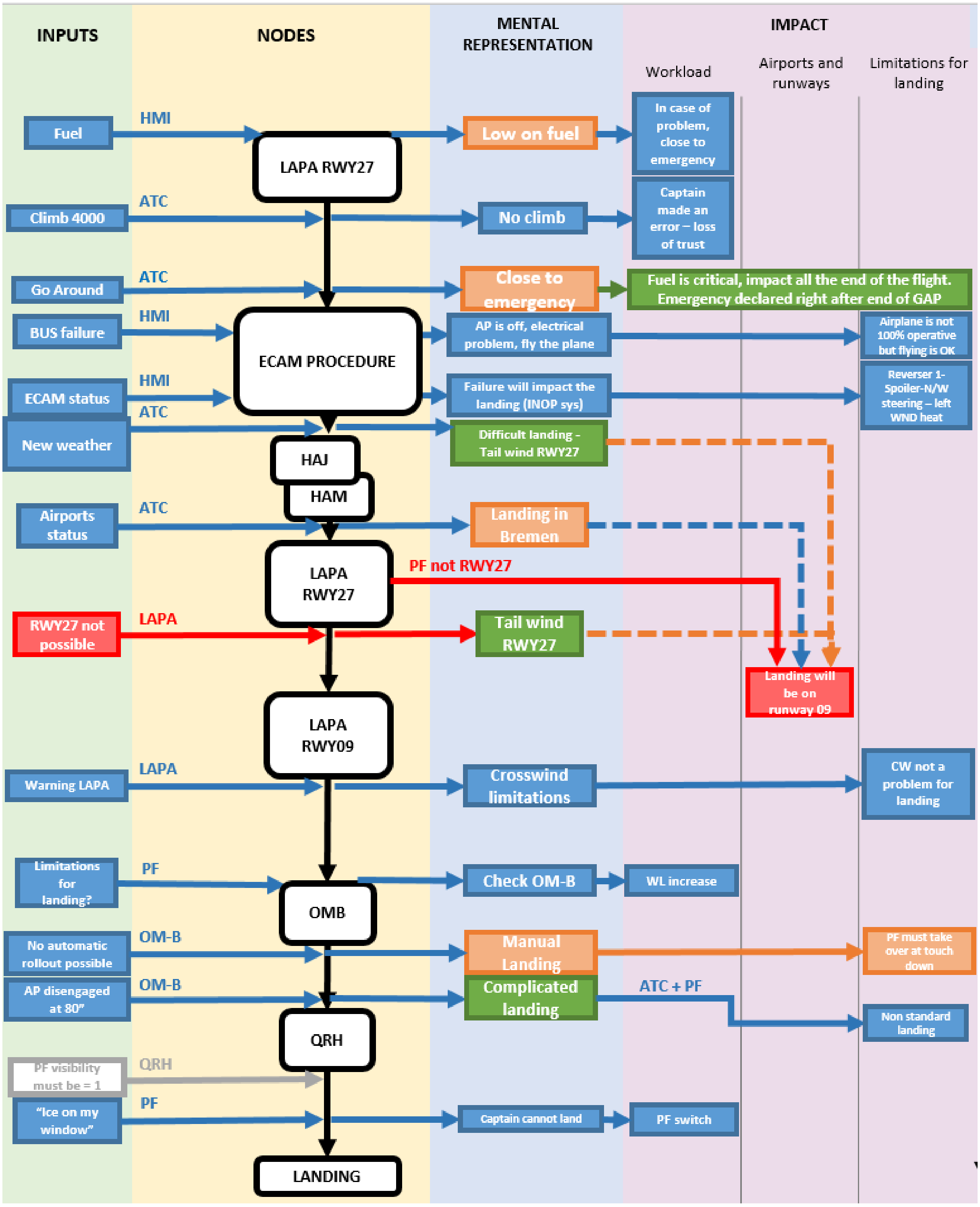


Figure 107: Pilot 25 Model

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

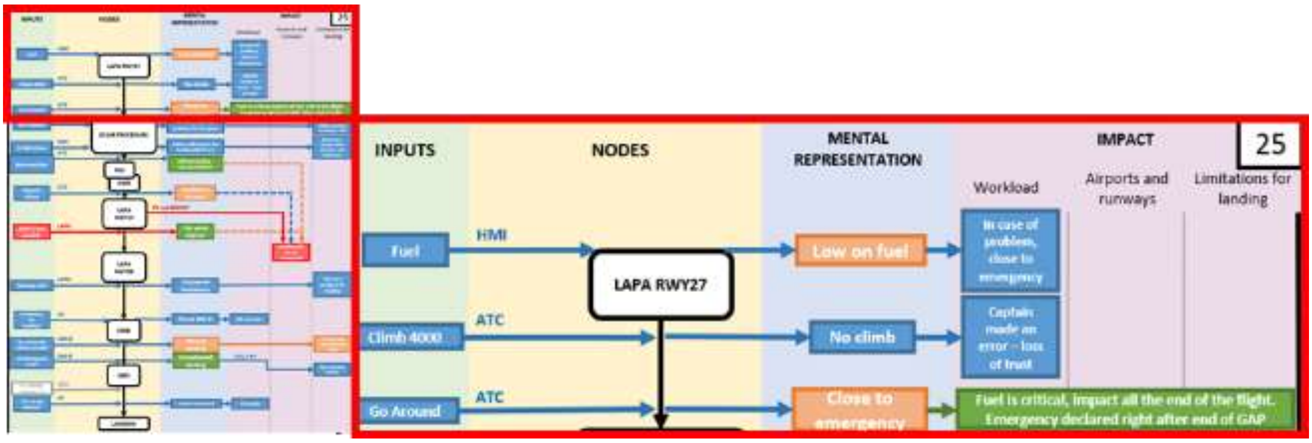


Figure 108: Model Part 1

For the input “Fuel” the co-pilot saw the amount of fuel remaining after evaluating the alternate airports. He declared Mayday one minute after mentioning the fuel quantity of 1.2T and the increased fuel flow due to the failure. They already had to perform the Go Around and suffered of an AC BUS 1 failure, hence the orange colour of the items in the MERIA model for “Low on Fuel” and “Close to emergency” . He estimated the remaining flight time with fuel quantity at 28 minutes (a bit more than 400kgs per 10min fuel flow). His mental representation of the fuel came late in the scenario but understood the impact it would have on the rest of the scenario.

When ATC asked them to climb to 4000 feet, the failure appeared almost at the same time. The co-pilot first turned off the alarm of AC BUS 1 failure, then turned the autopilot's vertical speed to +1200feet/min to climb to 4000 feet. That explains the blue colour of “No climb” item. Despite the alarm and the failure, he kept in his mental representation the tower's order to climb to 4000ft and did so as soon as he turned off the alarm.

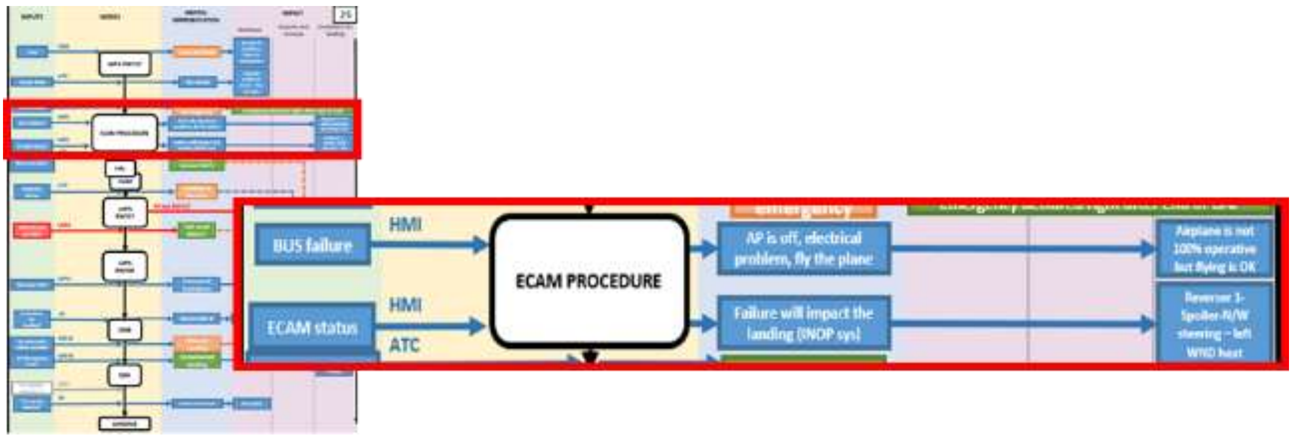


Figure 109: Model Part2

Future Sky Safety has received funding from the EU’s Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

During the ECAM resolution procedure, the captain has to disconnect the FAC 2 which disconnects the autopilot. The co-pilot held the side-stick in his hand and tried to reconnect quickly the Auto Pilot, which explains the blue colour of the item “AP is off, electrical problem, fly the plane” 

.

His mental representation during the ECAM resolution procedure was pretty good. He applied the first golden rule: Aviate, maintain control of the aircraft.

During the reading of the Inoperative Systems, the co-pilot identified that some of the inop systems will have a negative impact on the aircraft’s landing and braking performances, especially for Bremen short runway and, suggested to ask for latest wind information. And he made the connection between the current weather and its impact with inop systems. The colour of the item “Failure will impact the landing (INOP sys)” 

is therefore blue. He had a good mental representation of the failure’s impact and the weather degradation.

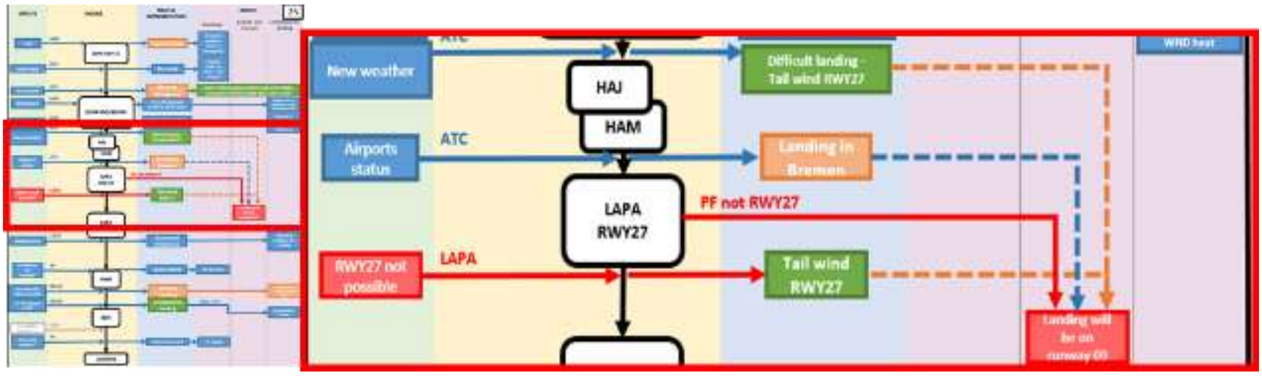


Figure 110: Model Part 3

With the weather degradation in Bremen the co-pilot evaluated the alternate airports before requesting ATC to fly back to Bremen. He proposed RWY 09 with the new wind orientation but his captain asked him to evaluate RWY 27 before. No LAPA for RWY 27 was calculated at that time. Items “Difficult landing – Tail wind RWY27” 

and “Tail wind RWY 27” 

colours are green but with an orange dotted arrow. In his mental representation, he had the difficulty of landing on RWY27 and the new wind orientation relative to the Bremen’s runway.

The first officer requested Hanover weather. ATC informed that Hanover and Hamburg are closed, but Bremen remains open with CAT II approach. He therefore proposed to his captain to ask ATC if there was an airfield with CAT I weather in the vicinity, before concluding with his captain to fly back to Bremen.

Item “Landing in Bremen” 

colour is orange with a blue dotted arrow. His mental representation was degraded by looking for an airfield nearby and not reconsidering Bremen as a possibility.

Future Sky Safety has received funding from the EU’s Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

Figure 111: Model Part 4

The LAPA calculation for RWY 27 asked by the captain took the first officer lot of time. He considered that the landing with the LAPA calculation was possible RWY 27, although he noted that there would be tailwind and not on RWY 09. This explains the red colour of the arrow leaving "RWY27 not possible"  pointing the green item "Tail wind RWY27" . The arrow leaving the node "LAPA RWY27"  is red because it was the captain that had to make the decision to land on RWY 09.

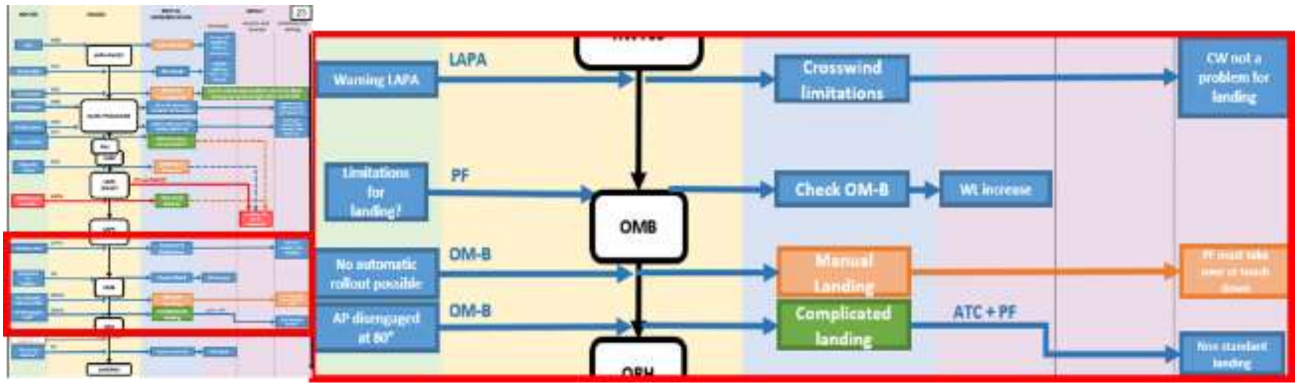
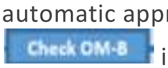


Figure 112: Model Part 5

After LAPA calculation for RWY 09, a warning message appear, indicating that the crosswind component for automatic roll-out on contaminated runway (4mm slush) is exceeded and, to check the OM-B. The co-pilot understood the message and checked the in OM-B for these limitations. The item "Crosswind limitations"  is therefore blue. By checking the OM-B, the first officer understood that they have to perform an automatic approach, disconnect the autopilot and, perform a manual roll-out. The item "Check OM-B"  is blue. His mental representations were good. He considered the warning message relevant and understood the limitations and what to do.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

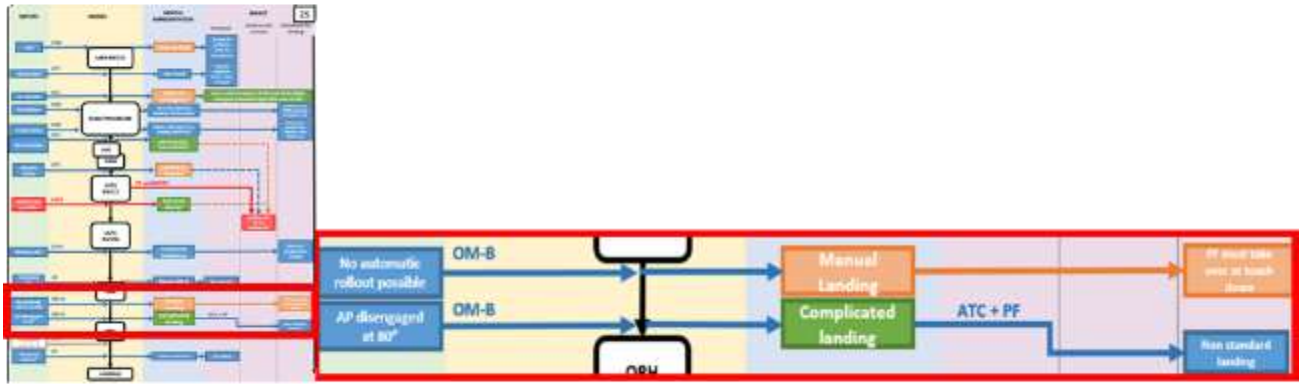


Figure 113: Model Part 6

"Manual landing" item is in orange cause the co-pilot didn't make the link between the manual roll-out imposed by OM-B due to crosswind and contaminated runway and, the manual roll-out imposed by the failure. The nose wheel steering inop system already forced the manual roll-out. His mental representation of the manual landing was degraded. He understood that it was imposed by the OM-B but did not make any connection with the inop system.

But he remembered that the nose wheel steering was inoperative and informed directly Bremen tower that they won't be able to leave the runway on their own. That's why the item "Complicated landing" is coloured in green. He had a good mental representation of the assistance needed on the ground.

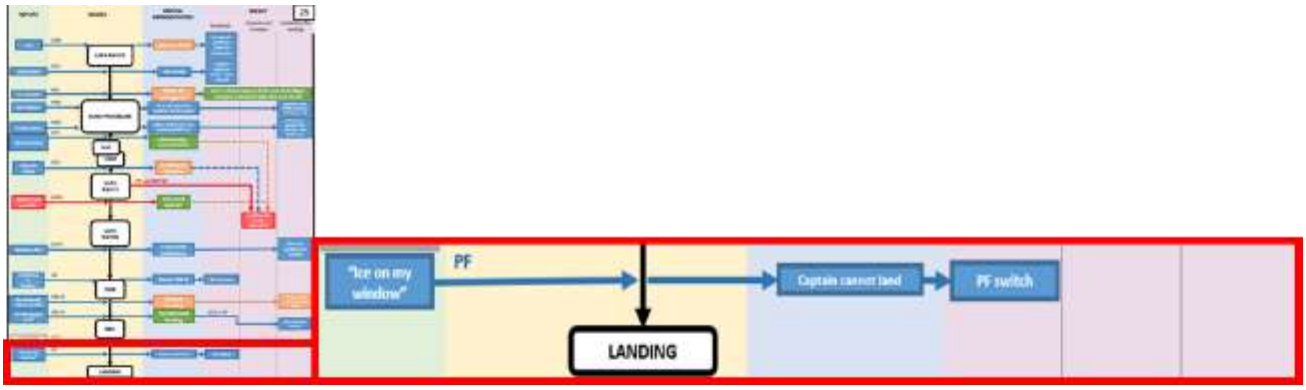


Figure 114: Model Part 7

On final approach the captain announced that he has ice crystals on the windshield and that he can't see outside. The co-pilot proposed to activate the anti-ice. He did not recall the left window and the windshield heat failure that was reminded to him by the captain. But he took control over the captain on his own. The item "Captain cannot land" is therefore in blue. He understood after the captain's call that he won't be able to do the landing. His mental representation that the captain could not land because of his zero visibility, was good, and took control over.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

For each MERIA model, the Mental Representation (MR) was synthesized in a table (Figure 115) in order to perform statistical analyses. As for the MERIA model, the blue colour corresponds to normal performance, green above normal, orange below normal and red corresponds to critical MR. It was coded in a 0-4 scale to perform the statistical analysis.

Pilot	Step	LowFuel	NoClimb	CloseEm	APoff	Failure	DiffLanding	LandBremen	TailWind	CWLimit	OMB	ManLand	CompLand	CaptNoLand
Pilot_1	1													
Pilot_2	1													
Pilot_3	1													
Pilot_4	1													
Pilot_5	1													
Pilot_6	1													
Pilot_7	1													
Pilot_8	1													
Pilot_9	1													
Pilot_10	1													
Pilot_21	2													
Pilot_22	2													
Pilot_23	2													
Pilot_24	2													
Pilot_25	2													
Pilot_26	2													
Pilot_27	2													
Pilot_28	2													
Pilot_29	2													
Pilot_30	2													
Pilot_31	3													
Pilot_32	3													
Pilot_33	3													
Pilot_34	3													
Pilot_35	3													
Pilot_36	3													
Pilot_37	3													
Pilot_38	3													
Pilot_39	3													
Pilot_40	3													

Figure 115: Phases of Mental Representation

We can see in Figure 116 that each item does not show the same trend according to the Steps. On the one hand most of these differences are not necessarily statically significant. On the other hand, the differences between the simulators used for steps 1 and steps 2 & 3, explain these differences.

To identify which cases we need to consider and which are not significant, we will use the Wilcoxon signed rank test under unpaired sample conditions with a p-value of 5%.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

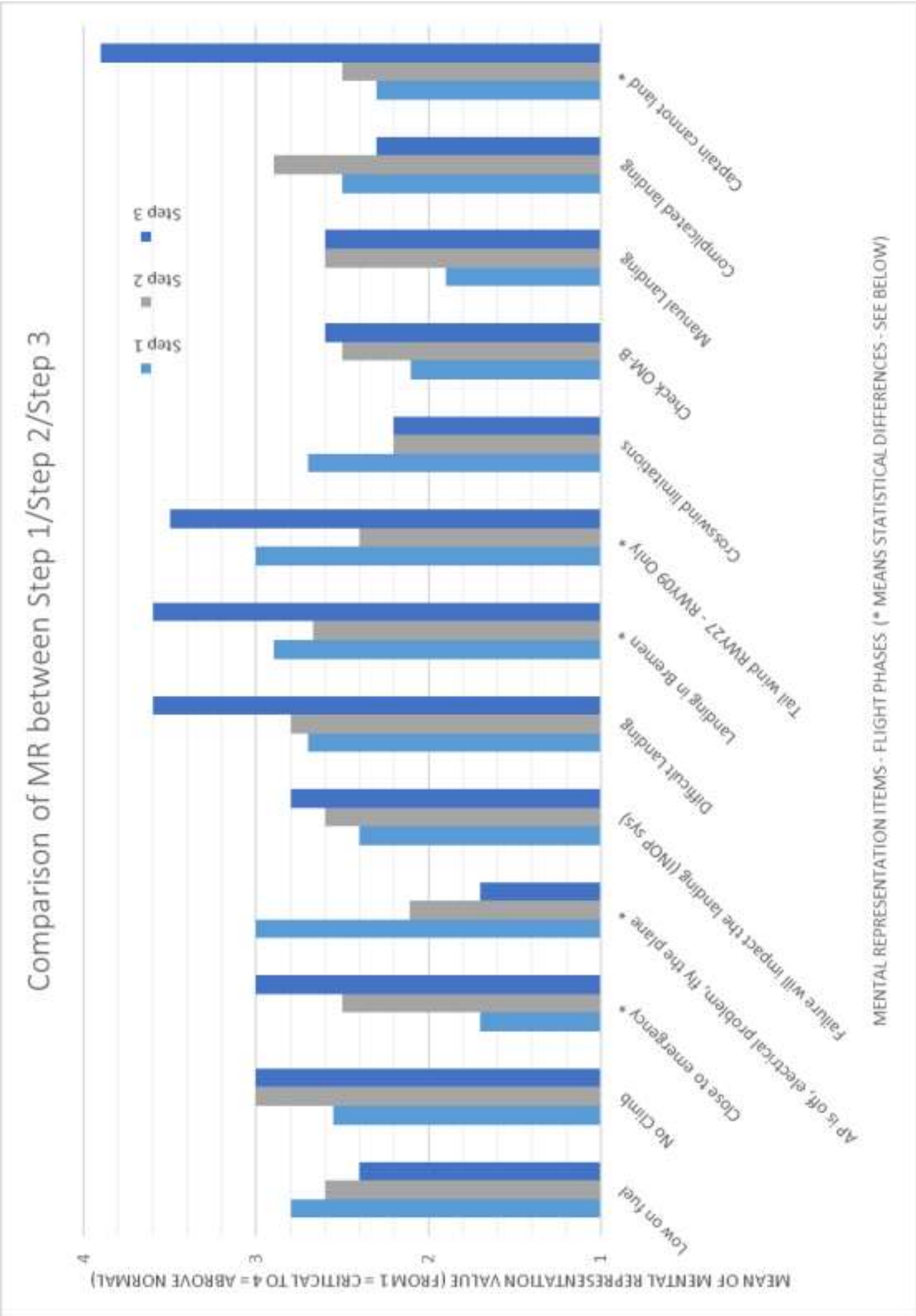


Figure 116: Mental representation

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

Let's take the example of the item "AP is off" shown in Figure 117. Statistically we have a difference between Step 1 and Steps 2&3, considering Step 1 and 2, p= 0.003278, and Step1 and 3 p= 0.0006506.

The captain asks gradually during steps 2&3 to the First Officer (subject of the experiment) to never take control of the simulator. Also, the" autopilot (AP) disconnect alarm" informing of the autopilot disconnection was not present during these steps. This explains the difference between the Steps but it is linked to a problem of representativeness of the simulator used and not to a scenario issue.

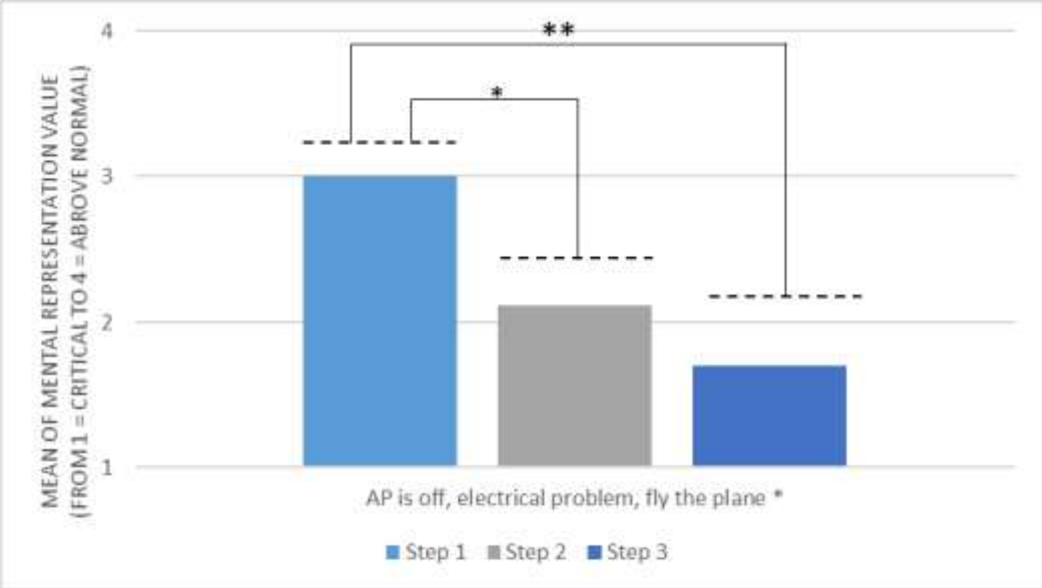


Figure 117: Detail of "AP is OFF"

What is interesting to note in Figure 118 is that during the first phase of the flight, the 3 steps are similar. There is no statistical difference between the pilots' representations. This is evaluated by "low on Fuel" item which is for the Fuel representation. However, the item "Close to emergency" is much better in Step 3 relatively to Step 1 p= 0.002983. This item takes into account the mental representation of the pilot's fuel consciousness in relation to the phase in which they have to perform the Go Around.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

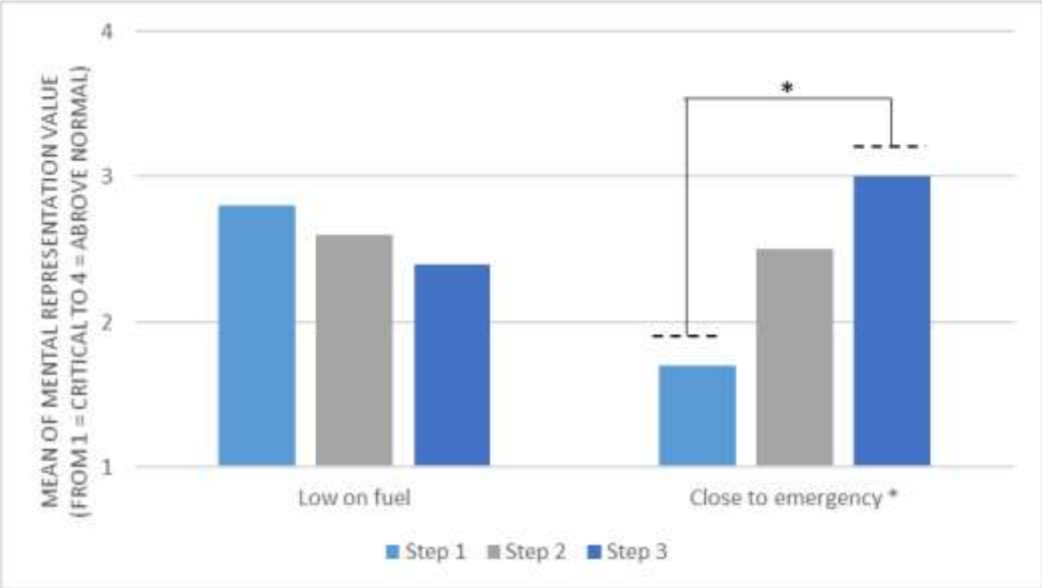


Figure 118: Detail of "Low on fuel" and "Close to emergency " item

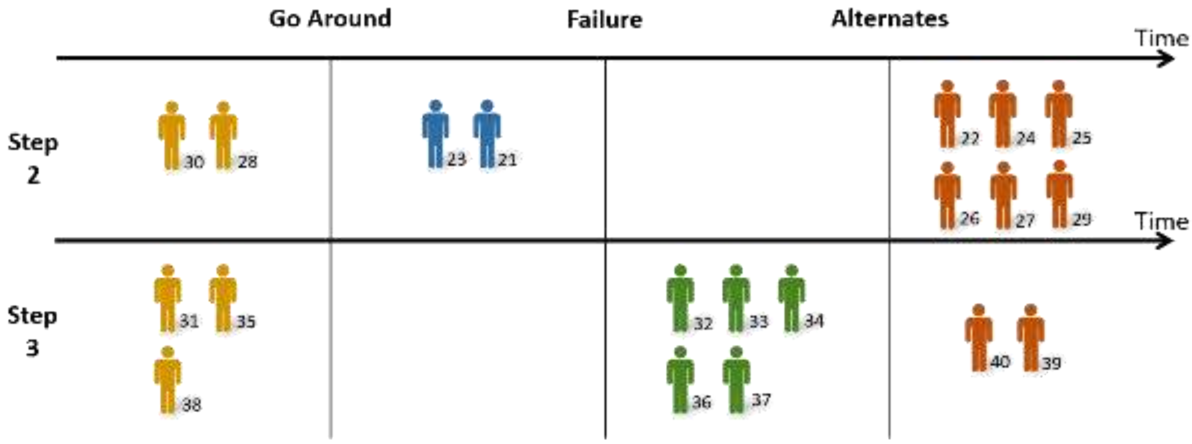


Figure 119: Chronological representation of fuel awareness

By crossing these data with the event frame, we obtain a chronological representation of fuel awareness (Figure 119) grouping the different pilots throughout the scenario. During the first approach (before the GA), the fuel level is not critical. Indeed, at the beginning of the scenario, they are about to land and the co-pilot knows that they've enough fuel to perform a Go Around. They have to do a Go Around and during this one a failure appears. Procedures require the co-pilot to "aviate" first and resolve the failure procedure. When the situation starts to be (very) critical (between Failure and Alternates evaluation), Step 3 interfaces has more impact to enhance mental representation of fuel level. This is confirmed with the items addressing the mental representation of available airports (Figure 120).

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

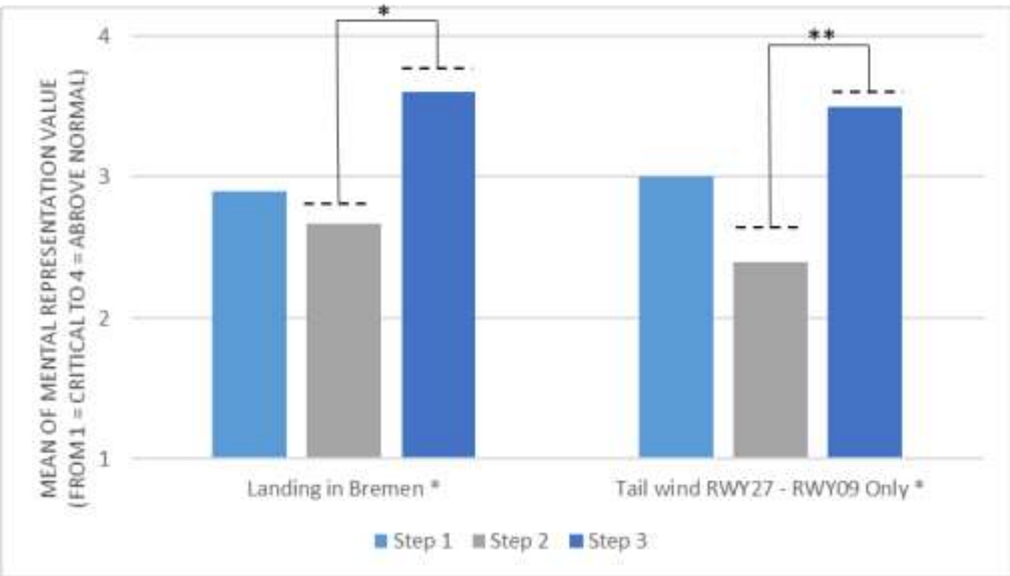


Figure 120: Detail of "Landing in Bremen" and "Tail wind RWY27 – RWY09 Only" item

In addition to the representation of fuel, the new interfaces used during Step3 allowed an improvement in the representation of the available airports (see “Landing in Bremen” item in Figure 120) (p=0.04653), thus identifying Bremen as the only possible airport for landing. This improvement can also be seen on the identification of runway 09 as the only option (p= 0.04973) (item “Tail wind RWY27 – RWY09 Only” in Figure 120). But we must keep in mind that this improvement of the mental representation of available runways is very closely related to an improvement on the mental representation of the weather conditions.

Another factor to take into account when choosing the airport and runway is the inoperative systems due to the failure. In order to improve the mental representation of the real state of the aircraft when it is in a degraded state, an interface has been developed in Step 3. It allows the pilot to better understand a failure and its repercussions. The "Captain cannot land" indicator (Figure 121) is linked to the limitation: the captain cannot land because of the formation of ice on his window. This indicator allows us to see if the pilots make the link between this limitation and the failure which has been explained earlier by the interface. The improvement brought by this interface is significant, either compared to Step 1 (p=0.0006052) or Step 2 (p=0.006653). The pilots keep in mind the limitations related to the failure and make the link between the limitation and its consequence when this one appears.

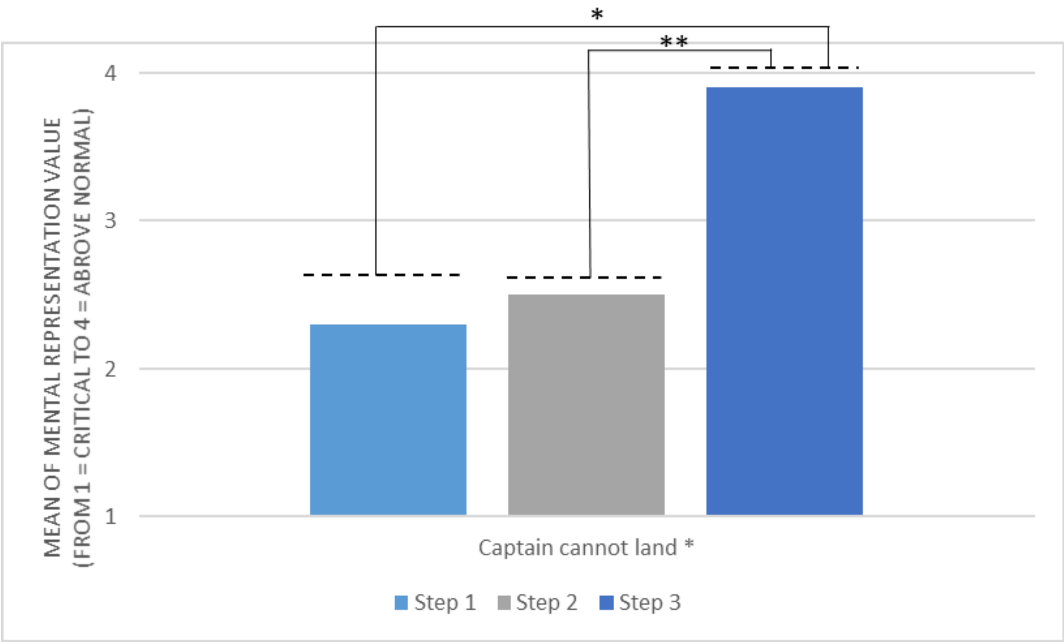


Figure 121: Detail of "Captain cannot land" item

2.14.2. Discussion

We can see that the implemented interfaces improve the HPE in the majority of the cases but some elements of the pilots' MR are degraded.

Take for example the orange and red circles that appear on the ND. The orange circle shows the flight distance reachable with 30min (1200kgs) of fuel remaining in the tanks. When they climb after the GA to 4000 feet, they have about 1600kgs of fuel left or 40min flight time. The orange circle thus shows at that time the achievable distance for the next 10 minutes, which represents almost 35NM to 40NM. At that time, they're at approximatively 7NM from Bremen. The scale chosen for the Navigation Display at that moment of the flight is between 5NM and 12NM, so the orange circle is beyond the display scale. The failure appears almost at that time of the flight which keeps the co-pilot focused between the ECAM display and his PFD and not the Navigation Display

The orange/red circles let pilots understand the available airport, and improve the fuel awareness but only at the critical moment. But the new HMI didn't bring an earlier understanding of the critical level of fuel due to the size of the circle (larger than the screen). HMI brings the right info at the right time (at the critical moment) and that improves their situation understanding.

If we consider the interface changes made on the faults and systems page inoperative we can draw several conclusions. The new ECAM page brings a better understanding of the failure and its consequences. Thanks that, pilots keep information in mind. They know by looking at the interfaces all the systems that are down at a glance. That improves the LAPA process. But cross different sources of information, like Cross Wind + Nose/Wheel Steering + REVERSER 1, is still misunderstood. We also need to

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

keep in mind the fact that the ECAM resolution is boxes to check directly on the screen allows the resolution procedure to be completed quickly. But the co-pilots lose the movements of the captain in their peripheral vision of what he is disconnecting or connecting. They thus lose a part of the complexity of the procedure and therefore the severity.

This new HMI should also help pilots to have a better representation of the weather, in order to be sure that this representation sticks to reality especially the weather on the ground at destination airport and alternates. The new tool with RWY available, improves their choices, but 20% of pilots do not understand the reason why the RWY are available or not, especially if these have changed over time between two checks.

2.15. Cross Comparison of Situation Awareness and Mental Representation

We analysed the HPE measurement methods to identify agreements and differences between metrics. We are particularly interested in the methods used to assess “situational awareness” – SA, “problem solving and decision making” – PS&DM. We compared this method with the one that analyses “mental representation”. We used the example of four pilots to understand these discrepancies, the pilots 29 and 30 having completed Step 2 and the pilots 32 and 40 having participated in Step 3. To understand the interest of this analysis we will explain the differences between the metrics. The measurement of "situational awareness" is done by experts who evaluated the pilots using the recording of their scenario. Scores given on a scale of 1 to 4 (1 corresponds to critical SA, 2 normal below, 3 normal and 4 above normal) are averaged to obtain an overall score per pilot and per phase. Situational awareness is assessed when the pilot must use this awareness to make a decision. The scoring process is the same for PS&DM. This PS&DM is evaluated by an expert who knows the scenario and its outcome, so the evaluation is made in relation to the expected consequences of the decision making. “Mental representation” – MR is measured using different sources of information (video, interviews, etc.) and evaluates the pilot's MR in relation to the expected MR.

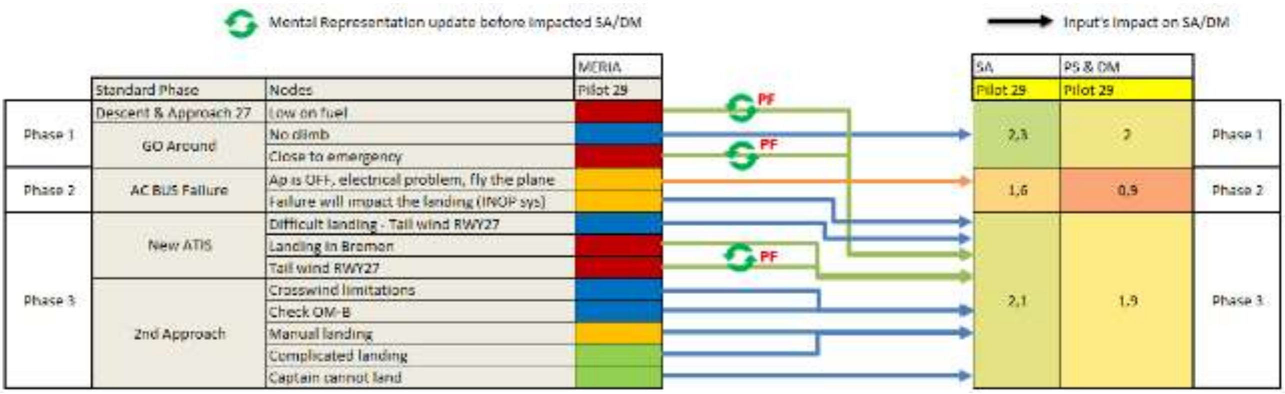


Figure 122: Pilot 29 Cross comparison

During the 1st phase the co-pilot had a pretty good Situation Awareness (SA) and a good Problem Solving (PS) & Decision Making (DM).

For the 2nd phase his SA and PS&DM was degraded as well as his Mental Representation.

During the 3rd phase the first officer still had no mental representation of the fuel. Therefore, the captain informed the co-pilot about the fuel level and enhanced his situation awareness. The co-pilot noticed the wind direction change but didn't mention Bremen RWY09. The decision to fly back to Bremen RWY09 was made by the captain. This enhanced the Problem Solving & Decision Making. For the rest of the Mental Representation items, we have a match with the SA and PS&DM.

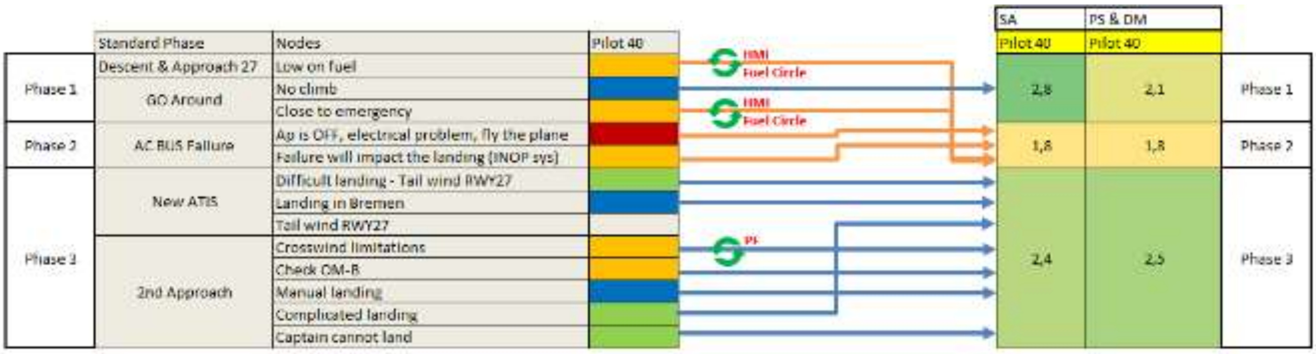


Figure 123: Pilot 40 Cross comparison

During the 1st phase the co-pilot had a really good Situation Awareness (SA) and a good Problem Solving (PS) & Decision Making (DM).

For the 2nd phase we can see that his Mental Representation was little degraded. Thanks the HMI fuel circle the co-pilot noticed the fuel level and this allowed him to have a pretty good SA and PS&DM.

During the 3rd phase the first officer had a good mental representation except for the items "Crosswind limitations" and "Check OM-B". The captain helped on these two items to find the information needed and understand it. The good mental representation and the help from his captain allowed him to have a good SA and PS&DM.

Here are the cross comparisons for the pilots 30 and 32 (Figure 124 and Figure 125).

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

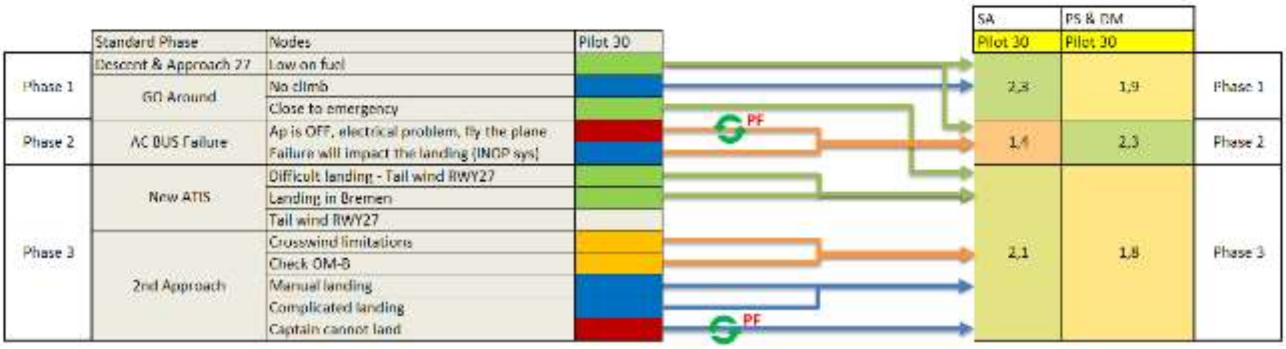


Figure 124: Pilot 30 Cross comparison

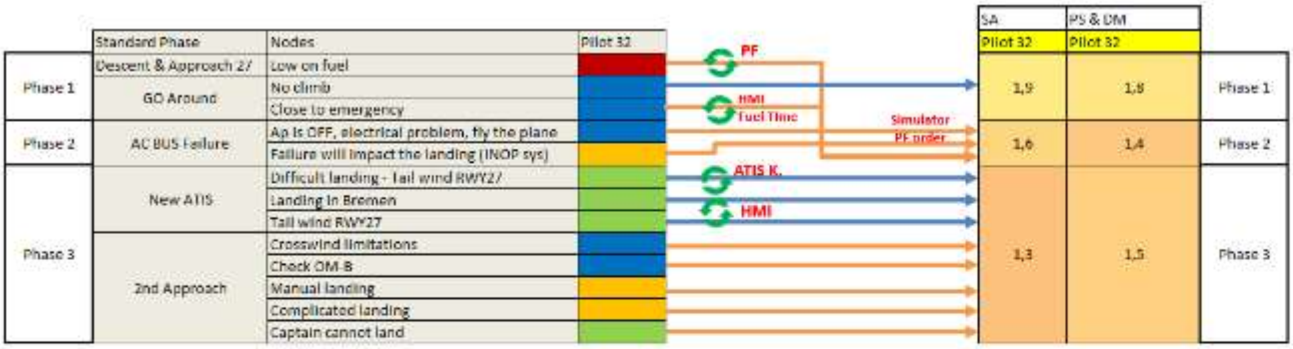


Figure 125: Pilot 32 Cross comparison

There are differences between the ratings, which is explained by the difference in methodology and the subtleties that exist between the elements collected and rated. Nevertheless, there is a similar attempt, of both ratings, of yield. Indeed, if we compare the interfaces used during step 2 and step 3 (Table 10), in phases 1 and 3 (before the failure and after the new weather) the interfaces tend to improve performance of MR and SA. However, in the phase between the failure and the new weather (phase 2), the interfaces tend to be less effective.

Table 10: Comparison of trends between SA and MR

	SIT AW.		MR	
Event	Step 2	Step 3	Step 2	Step 3
1	2,453	2,462	1,7	1,8
2	2,1	1,73	1,35	1,25
3	1,82	1,96	1,57	2,03

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

3 CONCLUSIONS

The following **Errore. L'origine riferimento non è stata trovata.** provides and overview about the different results and how they support the hypotheses. A "✓" within the table means that the results confirm the respective hypothesis, a "x" means that the results oppose the hypothesis, and a "o" means that the results neither confirm nor oppose the hypothesis. If no statement can be made, "n/a" is listed.

Table 11: Overview of results supporting the different hypotheses

Hypothesis	**Hypothesis supported by:**									
	Subjective data			**Pupil diameter**	**Eye-tracking**	**Timings**	**Competency evaluation**	**Benefits questionnaire**	**Performance curve**	**Cognitive walkthrough**
	WL	ST	SA							
The **Step 2** environment improves pilots' global HPE and performance compared to **Step 1**	o	o	✓	✓	✓	✓	✓	n/a	n/a	o
The **Step 3** environment improves pilots' global HPE and performance compared to **Step 2**	o	o	✓	✓	✓	✓	✓	✓	✓	✓
The enhanced mental representations in **Step 3** improve pilots' awareness about operational consequences of technical limitations in critical situations compared to **Step 1**	o	o	✓	n/a	✓	✓	✓	n/a	✓	✓
The enhanced mental representations in **Step 3** improve pilots' awareness about operational consequences of technical limitations in critical situations compared to **Step 2**	o	o	✓	n/a	✓	✓	✓	o	✓	✓

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

Final conclusions can be drawn with respect to every recorded data. The subjective recordings with respect to situation awareness of the pilots show a significant improvement with the new HMI of step 3 compared to the current HMI's of step 1 (Airbus A320) and step 2 (standard HMI of the AV2020 cockpit). Results on the pupil diameter support the value of the new ECAM actions display. The smaller pupil diameter observed with the AV2020 interface (Steps 2 and 3) support that the information is easier to find and to process. This is further supported by the results of the eye-tracking data. The eye-tracking analysis revealed that the pilots had much better situation awareness. The pilots obtained the relevant information directly from the displays in step 3. This was different in step 1 and 2. These results show that the new HMI provide the required information and, additionally, in a way that pilots are using them. The results of the competency analysis support this conclusion. They suggest that the pilots problem solving and decision making was improved in step 3 compared to step 1 and 2. The results of the competency analysis indicate an improvement in the ability of the pilots to acquire the relevant and accurate information necessary to analyse the given situation. Results on the timing also support the value of the new ECAM actions display. The localization on a same screen of all the necessary data and actions to perform speeds up the process and encourages the captain to complete all the actions by himself. Also the new interface is more efficient and certainly safer (change of PF/PM during the ECAM actions could favour errors). The display of inoperative systems with their consequences in terms of limitation prompts the crew to anticipate. Also the step 3 interface helps the crew to build a better situation awareness. Nevertheless this improvement in SA require more time.

Considering the variables that compose the theoretical model used to structure the "benefits questionnaire" analysis, it emerged that the "Perceived Usability" and "Ease of use" of the HMI lead towards a positive pilot's acceptance after the use of the new HMI. The different "Device-specific Features" considered in Step 2 and Step 3 affected the perceived usability and pilot's attitude after the use of the HMI. Positive effects were perceived for: reduction of workload in unexpected situations; improvement of situation awareness (e.g. artificial landscape); perceived usefulness for problem-solving (e.g. alternate airports, stay ahead of the plane); easing task execution (e.g. ECAM procedure) and, for Step 3 only, also in fuel awareness. All elements were relevant for safety operations. On the other hand, no negative effects on perceived workload, perceived situation awareness and perceived stress were identified by the pilots after the use of the interfaces. The more critical aspect from the pilot's perspective were the "Touch Screen" interface and the relation with automation: the appreciation of the touch screen interface was correlated with perceived benefits on the pilot's performance, but at the same time it presented still some concerns for safety to be further investigated and addressed for some specific tasks (e.g. extension of flaps). As for automation, pilots seemed to perceive more benefits for "fully-automated" solutions rather than the "partial automation" solutions currently experimented by pilots, suggesting that even further development of the HMI could be further investigated. In conclusion, it is possible to state that according to the pilots, the HMI is perceived to potentially improve pilot's performance and executive functions, by easing the HPE factors related to the piloting and monitoring tasks.

The results of the Performance Curve enabled to understand the way the HPE factors affected the performance, based on the pilots' self-assessed performance and in-depth review of the most challenging

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

parts of the interaction with the HMI. The performance curve analysis reported an increase in the alertness state of the pilots' right from the beginning of the session in Step 3, while during Step 2 pilots presented a state more similar to the A320 baseline. This immediate increase in alertness only for Step 3 can be related to an increase in the fuel awareness, evident as critical already from the beginning of the trial. In fact, the main implementation introduced for Step 3 according to the pilots, was the specific changes in the HMI to better show fuel information via the "ellipses". These changes to the HMI can be the responsible of the initial increase in alertness states in the pilots. Additional standardised and statistical models analysis could better corroborate the relationship between increased alertness perceived by the pilots, and this data can be used to better support the analysis performed on the mean heart rate variability of the pilots and their gaze distribution behaviours. The discussion with the pilots, centred around the performance curve tool, showed the potential of using qualitative data to integrate, complement and connect the different quantitative data used to measure the different HPE factors during the interaction with the new cockpit. This combination of the qualitative and quantitative data highlighted the impact of the different HPE factors and pilots' performance, leading to usable insights for the design of the new HMI including the Human Performance Envelope factors.

Overall, the results of step 1 and 2 show that certain elements of the mental representation were highly degraded (for example the awareness about the fuel status and the awareness about the operational consequences of technical failures). The new HMI developed within the project improved the HPE in the majority of cases and particularly in critical and complex situations where the pilots need additional support to be able to maintain the required level of safety.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

REFERENCES

Callan, D. J. (2016). Eye Movement Relationships to Excessive Performance Error in Aviation. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*. Retrieved from http://journals.sagepub.com/doi/abs/10.1177/154193129804201516

Cohen, J. (1960). A Coefficient of Agreement for Nominal Scales. *Educational and Psychological Measurement*, *20*(1), 37–46. https://doi.org/10/dghsrr

Duchowski, A. (2007). *Eye Tracking Methodology: Theory and Practice*. Springer Science & Business Media. Retrieved from https://books.google.com/books?hl=en&lr=&id=WtvVdNESRyIC&pgis=1

Ellis, K. (2009). Eye tracking metrics for workload estimation in flight deck operations. *Theses and Dissertations*. Retrieved from http://ir.uiowa.edu/etd/288

Glenstrup, A., & Engell-Nielsen, T. (1995). *Eye controlled media: Present and future state*. Retrieved from https://pdfs.semanticscholar.org/dc8b/c8a76e8047641bd5abf8c0f53b59bff76349.pdf

Jacob, R., & Karn, K. (2003). Eye tracking in human-computer interaction and usability research: Ready to deliver the promises. *Mind*. Retrieved from http://scholar.google.co.uk/scholar_url?url=https%3A%2F%2Fpdfs.semanticscholar.org%2F5f1f%2F69d3f8807a5abc490955823ecfec55b15bb9.pdf&hl=en&sa=T&oi=ggp&ct=res&cd=1&ei=95qhWPb7MomVmAGK2JPAAg&scisig=AAGBfm0guMKU26x9F8V7SWpSiPIZw0oqXQ&nossl=1&ws=1670x896

Nakayama, M., & Shimizu, Y. (2004). Frequency analysis of task evoked pupillary response and eye-movement. *Proceedings of the Eye Tracking Research & Applications Symposium on Eye Tracking Research & Applications - ETRA'2004*, 71–76. http://doi.org/10.1145/968363.968381

Salvucci, D. D., & Goldberg, J. H. (2000). Identifying fixations and saccades in eye-tracking protocols. In *Proceedings of the symposium on Eye tracking research & applications - ETRA '00* (pp. 71–78). New York, New York, USA: ACM Press. http://doi.org/10.1145/355017.355028

Stephane, A. L. (2012). Eye tracking from a human factors perspective. In G. A. Boy (Ed.), *The Handbook of Human-Machine Interaction: A Human-Centered Design Approach*. Ashgate Publishing, Ltd. Retrieved from https://books.google.com/books?hl=en&lr=&id=inJ7BgAAQBAJ&pgis=1

Wickens, C., Xu, X., Helleberg, J., & Marsh, R. (2001). Pilot visual workload and task management in freeflight- A model of visual scanning. *Focusing Attention on Aviation Safety*. Retrieved from https://scholar.google.co.uk/scholar?q=pilot+visual+workload+and+task+management&btnG=&hl=en&as_sdt=0%2C5#0

Yu, C.-S., Wang, E. M.-Y., Li, W.-C., Braithwaite, G., & Greaves, M. (2016). Pilots' Visual Scan Patterns and Attention Distribution During the Pursuit of a Dynamic Target. *Aerospace Medicine and Human Performance*, *87*(1), 40–7. http://doi.org/10.3357/AMHP.4209.2016

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

Appendix A TRANSCRIPTIONS OF PILOTS FROM THE AC BUS FAILURE TO THE END OF LIMITATIONS

Pilot 21

Timecode	Speaker	Transcript
00:27:59	S1	Lufthansa 2487, turn 3,000 left turn heading 100.
00:28:04	S2	Yeah. Altitude mode and [inaudible 00:28:05] and left turning 100.
00:28:09	S1	Yeah. Speed **checked** flaps 0.
00:28:19	S2	You can perhaps ask him any idea how long the delay will be.
00:28:26	S1	Yeah, if we… Lufthansa 2487, if I can ask at all how long the work will be… take place on the runway?
00:28:35	S3	Actually, we are finished right now, we're very sorry for the go around. We actually finished right now. Expect… Just continue and call me whatever your intentions are.
00:28:48	S1	Lufthansa 2487, to call you back shortly.
00:28:51	S2	Of course.
00:28:52	S1	Okay. **Fuel** on board is now 1,500 now. Yeah, I'll tell him new approach. Lufthansa 2487 requesting approach.
00:29:01	S3	Okay. You get the new approach Lufthansa 2487.
00:29:07	S1	AC BUS 1 fault.
00:29:09	S2	Okay. You have control?
00:29:12	S1	I have control.
00:29:13	S2	I lost my indications. Okay.
00:29:18	S1	AC BUS 1 fault. I have control.
00:29:19	S2	You have control. I don't know how to get the checklist.
00:29:24	S1	I have to push a second time.
00:29:26	S2	Push a second time, that's (Overlapping Conversation).

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

00:29:27	S1	Yeah. Now it's here.
00:29:29	S2	So, you have control…
00:29:30	S1	I have control.
00:29:31	S2	…autopilot, is everything under control, safe altitude?
00:29:35	S1	Yeah, it's a safe flight path as we're heading 110.
00:29:40	S2	Okay. So, when you are ready for ECAM actions, just tell me.
00:29:43	S1	ECAM actions.
00:29:44	S2	AC BUS 1 fault. AC BUS 1 seems to be inop. Okay. Lower override. Generator 1 off.
00:29:57	S3	Lufthansa 2487, please climb 4,000.
00:30:02	S1	Lufthansa 2487…
00:30:03	S2	(Overlapping Conversation).
00:30:04	S1	Yeah.
00:30:05	S2	Excuse me.
00:30:07	S1	For the 2487, climb 4,000 feet.
00:30:10	S2	Generator 1 recovered? No. Can you check?
00:30:15	S1	[inaudible 00:30:15] 4,000.
00:30:25	S2	Generator not recovered.
00:30:28	S1	It's not recovered.
00:30:31	S2	Okay. Generator 1 off.
00:30:34	S1	I'll change the autopilot, it's not climbing.
00:30:36	S2	(Overlapping Conversation) won't be working, so you have now two autopilots, so never mind.
00:30:42	S1	Mm-hmm. So, then it's…
00:30:45	S2	FAC2 off.
00:30:48	S1	So, it's not climbing 4,000.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

00:30:52	S2	FAC2 on.
00:31:01	S1	Is FAC2 recovered?
00:31:02	S2	Is FAC2 recovered? We cannot see it.
00:31:05	S1	You cannot see it (Overlapping Conversation), it's just… it's just not climbing although I entered 4,000 feet, but it's still safe to continue at 3,000 here.
00:31:14	S2	Yeah, so continue. I'll tell him. Lufthansa… What is the call sign?
00:31:21	S1	2487.
00:31:22	S2	2487, for technical reasons, we have to stay in 3,000 feet please.
00:31:27	S3	Okay, stay in 3,000, that's fine with us. And call me for further intentions.
00:31:32	S2	Roger, standby. So, auto flight, autopilot off (Overlapping Conversation).
00:31:38	S1	So, 3,000…
00:31:42	S2	Okay. Auto flight autopilot off, **make it**. AC Essential BUS alternate. Autopilot says on but never mind, and I got my (Overlapping Conversation).
00:31:54	S1	Screens recovered, yeah.
00:31:56	S2	ATC transponder system 2, end of procedure, 11 of 11. ECAM actions completed. Clear?
00:32:06	S1	Clear.
00:32:10	S2	Okay. System is… Everything is recovered. Generator 1 is inop.
00:32:17	S1	It is inop.
00:32:17	S2	But the AC BUS 1 seems to be operating. That's a little bit astonishing.
00:32:21	S1	Mm-hmm.
00:32:22	S2	Okay?
00:32:22	S1	But it's working through the… Yeah.
00:32:25	S2	I don't know, (Overlapping Conversation).
00:32:26	S1	Autopilot is still engaged.
00:32:28	S2	You're still autopilot flying?

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

00:32:29	S1	Yeah, **five star**.
00:32:29	S2	Inop systems. Inop systems, landing distance, slats slow, CAT II only. FAC1, [inaudible 00:32:40] not important, two elec pumps not important. Left windshield heat, left window heat, radio altimeter that's not important, (Overlapping Conversation) is important.
00:32:49	S1	[inaudible 00:32:49] that's important, yeah.
00:32:51	S2	CAT III is written here already. Generator 1, spoiler 3 not too important, blue hydraulic, nose wheel steering might be important.
00:33:00	S1	Yeah, that's important.
00:33:00	S2	Okay?
00:33:01	S1	Yeah.
00:33:02	S2	So ECAM actions completed… Sorry, procedure is completed. I cannot **clear** [inaudible 00:33:08].
00:33:09	S1	This remains… Okay, we have an occasion of… this is all important for the landing, the reverser on the steering and the spoiler
00:33:18	S2	So, I would say I have control again.
00:33:21	S1	You have control.
00:33:23	S2	And next step would be to check OMB.
00:33:27	S1	Yeah.
00:33:28	S2	Expanded procedure, is there anything more (Overlapping Conversation).
00:33:31	S1	Is there anything more, and just keep an eye on the field, we have still 1,400…
00:33:35	S2	Yeah, 40 minutes.
00:33:37	S1	Yeah, 40 minutes, yeah.
00:33:38	S2	So, I clear, I clear AC BUS 1 fault here?
00:33:40	S1	Yeah.
00:33:42	S2	All cleared please. We don't have a heading mode, please confirm the heading.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

00:33:49	S1	Lufthansa 2487, confirm are still on heading 110?
00:33:54	S3	Yeah, you were supposed to fly heading 100 but fly heading **0910** now.
00:33:59	S1	Lufthansa 2487 heading **0910.**
00:34:05	S3	It's correct.

Pilot 30

Timecode	Speaker	Transcript
00:25:00	S1	Just a second. Give me your headphone. **Hans**, you switched it off intenti– …oh, unintentionally. So we make a choice for [inaudible 00:25:09].
00:25:10	S2	Oh, radio check, 1221.
00:25:15	S1	(Overlapping conversation)
00:25:15	S3	Lufthansa 1221. Do you read?
00:25:17	S1	Lufthansa 1221, I read you, five. (Overlapping conversation)
00:25:20	S3	Okay. Turn left heading 100 and climb 4,000 please.
00:25:24	S1	Left turning 100, climbing 4,000, Lufthansa 1221. Should we remain in the frequency?
00:25:30	S3	Change over to frequency 129.9. Bye-bye.
00:25:33	S1	[inaudible 00:25:33] Lufthansa 1221. What is this? I'm losing my screen. Okay.
00:25:40	S2	AC BUS 1 fault. I don't have a screen. You have control.
00:25:44	S1	I have control? Okay. So we are climbing 700 feet up to 4,000 and it's not working. I select 1,000. Is it okay if we are climbing 4,000?
00:25:55	S2	Yeah, sure.
00:25:56	S1	Okay.
00:25:56	S2	You have that clearance for 4,000.
00:25:57	S1	Okay. But it's not….

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

00:25:59	S2	I know it takes a second. It takes (overlapping conversation). Good.
00:26:00	S1	Okay. Good.
00:26:01	S2	You're still in altitude mode, perhaps pull it long and slowly.
00:26:09	S1	Vertical speed?
00:26:10	S2	Yeah, vertical speed. No. (Overlapping conversation)
00:26:12	S1	Okay. So the autopilot is still working?
00:26:15	S2	Yeah. Autopilot screen.
00:26:16	S1	Okay. We are….
00:26:18	S2	I help you. I help you. (Overlapping conversation)
00:26:19	S1	Thank you very much.
00:26:20	S2	So that's it.
00:26:22	S1	We are [inaudible 00:26:22] and we're climbing 4,000 in the area of **Bream**. Fuel situation's a little bit critical, 1.5.
00:26:28	S2	Yeah.
00:26:30	S3	Lufthansa 1221, please change over to 129.9. Bye-bye.
00:26:32	S2	1221. Just give me a second. Okay. So, you have RT?
00:26:38	S1	Yeah. I cannot switch to the (overlapping conversation).
00:26:39	S2	Okay. I'm already on 1229. So you can call them and I'll set the frequency.
00:26:43	S1	I'll call (overlapping conversation).
00:26:45	S2	Okay.
00:26:45	S1	Okay. [inaudible 00:26:46] Lufthansa 1221 [inaudible 00:26:48] climbing 4,000 [inaudible 00:26:50] 3,500.
00:26:52	S3	Lufthansa 1221, my apologies for the go-around. Fly heading 090 please and maintain 4,000.
00:27:00	S1	Lufthansa 1221, left turn heading 090. Okay. So, aircraft is set. We are at the area of [inaudible 00:27:08] and we have AC BUS 1 fault.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

00:27:12	S2	Yeah.
00:27:13	S1	ECAM action of the situation [inaudible 00:27:15].
00:27:16	S2	Yeah.
00:27:16	S1	We have alt [inaudible 00:27:16].
00:27:17	S2	Please push onto the field of AC BUS 1 fault when I get the ECAM actions. Thank you very much.
00:27:23	S3	You're welcome.
00:27:24	S1	ECAM actions, AC BUS 1 fault. Lower override. Generator 1 off. Generator 1 on. Ge–…is Generator 1 recovered? Yes or no?
00:27:39	S2	No.
00:27:40	S1	No? Generator 1 off. FAC2 off. FAC2 on. You cannot see it? But usually, it's…
00:27:56	S2	It's recovered.
00:27:56	S1	…successful.
00:27:57	S2	Okay.
00:27:57	S1	Recovered? Yes.
00:27:59	S2	So it's [inaudible 00:27:59]. Okay.
00:28:01	S1	Autoflight, autopilot is off. You have to fly manually.
00:28:05	S2	Okay.
00:28:07	S1	AC essential feet alternate. ATC 2. AC BUS 1 fault, ECAM actions completed.
00:28:20	S2	Okay.
00:28:22	S1	Clear?
00:28:22	S2	Clear. AC BUS 1, fault.
00:28:25	S1	Perfect. So system page is what we have seen. The Generator 1 is inop.
00:28:31	S2	Okay.
00:28:31	S1	AC BUS 1is inop.
00:28:32	S2	Okay. So we should start the APU if we are missing one generator?

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

00:28:36	S1	Yes.
00:28:36	S2	Does that make sense?
00:28:37	S1	[inaudible 00:28:37] So I will have my screen back. Due to the AC essential feet.
00:28:42	S2	Uh-huh.
00:28:42	S1	And I would like to continue flying.
00:28:44	S2	Okay. So….
00:28:45	S1	I have put on the auto–…could you please put on the autopilot? And after, I will take. Put it on [inaudible 00:28:52] again. Okay. That's good. That's good.
00:28:56	S2	Okay.
00:28:57	S1	Everything is [inaudible 00:28:57]. I have control.
00:28:59	S2	You have control. We just have to descend back 4,000.
00:29:02	S1	Yeah. It's okay. We're now in altitude mode. It seems to be okay. Okay, please continue with limitations, set inop systems.
00:29:09	S2	Inop systems, pack 1. Left tank pump one, right tank pump one.
00:29:17	S1	Tell me only what is important for the flying.
00:29:19	S2	Oh, okay. So reverse one is inop and we don't need CAT III. Nose wheel steering is inop. That's probably a little bit important, that one, to get pulled off from the runway.
00:29:31	S1	Okay. You can call him already.
00:29:36	S2	Tell the tower?
00:29:37	S1	Yeah.
00:29:37	S2	Okay.
00:29:38	S1	[inaudible 00:29:38]
00:29:38	S2	So, [inaudible 00:29:39] for later on for your pre planning. We need a tow truck to get us pulled off the runway because we will stop on the runway since nose wheel steering is not working.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

00:29:48	S3	Lufthansa 1221, it's copied. I contact tower.
00:29:51	S2	Okay. Should we already jump back to [inaudible 00:29:53] since fuel is getting…or do we have time?
00:29:56	S1	Very good idea. No, we'll make it.
00:29:58	S2	Okay. Lufthansa 1221, fuel situation. We appreciate redirect us direct to [inaudible 00:30:04] the ILS.
00:30:07	S3	Okay. You can turn back heading north now, Lufthansa 1221.
00:30:13	S2	Heading north, Lufthansa 1221. The runway situation is still unchanged? It's still wet?
00:30:22	S3	Lufthansa 1221, are you talking to me?
00:30:25	S2	Lufthansa 1221, I just wanted to know that the runway condition is still wet and that there is no snow.
00:30:31	S3	Okay then. Lufthansa 1221, I just checked. There's a new **RTAs** out. It's information Kilo. Please check whether there's information Kilo.
00:30:41	S2	1221, checking Kilo. Should we already ask for 3,000 or…?
00:30:45	S1	No, not yet.
00:30:46	S2	Okay. Cool.
00:30:48	S1	Wait a second. Where's the **RTAs**? First, we continue the limitations, please. (Overlapping conversation)
00:30:52	S3	Lufthansa 1221, turn left heading 270 and I keep you in the vicinity of the airport.
00:31:00	S2	Appreciate that, left heading 270, Lufthansa 1221. So, for landing, which is important now? Let me just push it, the procedure.
00:31:11	S1	So we have to make it new of course, okay.
00:31:13	S2	Okay. So after we have finished it, what's the [inaudible 00:31:16]?
00:31:16	S1	No. First, first, we continue all the ECAM and make the next step.
00:31:20	S2	Slats slow.
00:31:21	S1	Okay.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

00:31:23	S2	So, a bit more time doing the approach. And then, navigation, CAT II only.
00:31:29	S1	Okay, CAT II only. Fine. So this is completed?
00:31:33	S2	Mm-hmm.
00:31:34	S1	Please clear the system page. We don't need it anymore. Clear the system page (overlapping conversation).
00:31:38	S2	Oh, thank you very much.
00:31:40	S1	Welcome. And now, we can concentrate on the **RTAs** as next step.
00:31:44	S2	Okay. So, for the procedure, we don't have to check. That's fine.
00:31:50	S1	We make it. But first, we take a look on the **RTAs**.
00:31:52	S2	Okay.
00:31:53	S1	First, the procedure and make [inaudible 00:31:53].
00:31:54	S2	160 with 80 knots. So it's more cross [inaudible 00:31:57].
00:31:59	S1	Yeah.
00:31:59	S2	500 [inaudible 00:31:59] 200.

Pilot 38

Timecode	Speaker	Transcript
00:24:04	S1	Wait a second.
00:24:04	S2	Lufthansa 1221, did you call in?
00:24:06	S1	Lufthansa 1221, we are on the [inaudible 00:24:09] approach at 3,000 feet.
00:24:11	S2	Lufthansa 1221, turn left heading 100 and climb 4,000 ft. Sorry for the go-around.
00:24:19	S1	Lufthansa 1221, left turn heading 100, climb 4,000 ft. Left turn heading 100 or 110? Confirm heading?
00:24:30	S2	Lufthansa 1221, left turn heading 100.
00:24:34	S3	Oh, sorry.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

00:24:34	S1	Left turn heading 100, Lufthansa 1221.
00:24:37	S3	That's copied. Okay.
00:24:40	S1	Okay, 40 minutes endurance.
00:24:43	S3	Forty minutes? It is not too much, no?
00:24:45	S1	No.
00:24:48	S3	AC BUS 1 fault.
00:24:50	S1	There's the ECAM message, AC BUS 1 fault.
00:24:51	S3	I don't have a screen. You have control.
00:24:53	S1	I have control. AC BUS 1 fault. Okay. Still in…autopilot is active. Autopilot blue, vertical speed mode. Aircraft is flying fine. Heading mode is also good. Okay. Then, ECAM actions?
00:25:11	S3	Yeah, I cannot activate it. Please push the ECAM one in. Thank you. [inaudible 00:25:16]
00:25:18	S1	Okay. ECAM actions, AC BUS 1 fault, lower override. Generator 1 off. Generator 1 on. Is generator 1 recovered? Yes or no?
00:25:35	S3	Generator 1 negative.
00:25:38	S1	No? Generator 1 off. FAC 2 off. FAC 2 on. So FAC 2 is off. Manual flight. Autopilot's off. Is FAC 2…?
00:25:55	S3	(Overlapping conversation) recovered.
00:25:57	S1	FAC 2 is recovered. It's working again.
00:25:59	S3	Okay. So….
00:26:01	S1	Autoflight, autopilot is off. AC essential feed alternate. This works.
00:26:11	S3	Okay.
00:26:12	S1	ATC transponder system 2. ECAM actions completed.
00:26:19	S3	Okay.
00:26:20	S1	Clear?
00:26:20	S3	Then clear ECAM.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

00:26:22	S1	Clear ECAM.
00:26:22	S3	And I would try to reset the autopilot.
00:26:25	S1	Yeah.
00:26:29	S3	Autopilot blue, uh, green, speed heading alt.
00:26:33	S1	Perfect.
00:26:34	S3	Auto thrust green.
00:26:35	S1	Manual?
00:26:37	S3	I would like to continue flying.
00:26:40	S1	Okay. You have all indications?
00:26:40	S3	I have control.
00:26:41	S1	You have control?
00:26:42	S3	I have control. Continue with system page.
00:26:47	S1	System page, elec. All systems recovered. Generator 1 is off. Generator 2 took it over.
00:26:53	S3	Good.
00:26:53	S1	Every system is supplied. Clear ELEC.
00:26:55	S3	Clear ELEC?
00:26:55	S1	Clear ELEC.
00:26:59	S3	Inop systems and limitations.
00:27:01	S1	Inop systems, blue hydraulic, limitations. Slats slow, slats slow. Inop system reverser 1 and spoiler 3. Landing distance.
00:27:12	S3	Yeah, the landing distance seems to be [inaudible 00:27:14] slow on the approach. Okay.
00:27:17	S1	Nose wheel steering in crosswind, expect latitude control problem.
00:27:23	S3	Lateral control problem.
00:27:24	S1	Lateral control. (Laughter)

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

00:27:25	S3	Okay.
00:27:25	S1	That's a nice indication.
00:27:27	S3	Do we have crosswind enough?
00:27:29	S1	In…yeah, we have 15 knots in [inaudible 00:27:31].
00:27:33	S3	Or? This is crosswind or…?
00:27:35	S1	Crosswind. There was crosswind indication.
00:27:37	S3	Okay. So we have to think about it, okay?
00:27:38	S1	Yeah.
00:27:39	S3	Continue.
00:27:40	S1	Then left windshield heat and left window heat, in icy conditions, right pilot flying only. Right now, we are in clouds.
00:27:49	S3	Yeah, I cannot see anything now.
00:27:51	S1	No **icy** right now?
00:27:53	S3	[inaudible 00:27:53]
00:27:54	S1	Yeah.
00:27:55	S3	Okay, continue.
00:27:56	S1	Then left tank pump 1, right tank pump 1, and blue elec pump.
00:28:01	S3	Okay.
00:28:04	S1	Radio altimeter 1, pack 1, and generator 1.
00:28:08	S3	Okay. Mm-hmm. (Overlapping conversation)
00:28:14	S1	So, CAT III inop and CAT II only.
00:28:16	S3	That's important. Okay, fine.
00:28:19	S1	Good.
00:28:20	S3	Good. Then please check in OMB, expanded procedure, AC BUS 1 fault, whether there might be anything interesting. Just read it quickly for you silently. If it's anything important, tell me what we have to watch in the [inaudible 00:28:37] in the OMB. Is other inop systems not displayed on

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

		ECAM?
00:28:44	S1	Okay. ELEC, AC BUS 1 fault.
00:28:49	S3	**Tell me**…silently. Only if it's interesting.
00:28:51	S1	Okay.
00:28:52	S3	And….
00:28:52	S1	All right.

Pilot 40

Timecode	Speaker	Transcript
00:23:00	S1	266 **upbound** to 2.2 [inaudible 00:23:03] and then a left turn direct to [inaudible 00:23:05], yeah.
00:23:06	S2	Lufthansa 1221, change over to frequency 129.9 again, and sorry for the go around.
00:23:12	S1	Speed flaps 1. Lufthansa 1221, 12-… Lufthansa 1221 129.9, no worries.
00:23:28	S2	Lufthansa 1221, that's copied. Sorry for the go around. Climb to 3,000 for now and turn left heading 100.
00:23:41	S1	Lufthansa 1221, we're climbing 3,000 and left turning 100.
00:23:45	S3	[inaudible 00:23:45]
00:23:49	S1	And primary radar I don't know if I checked in. We are passing 3,000 and we're turning left heading now.
00:23:54	S2	Yeah. Lufthansa 1221, turn left heading 100 and climb 4,000 feet.
00:24:00	S1	Lufthansa 1221, heading 100 climbing 4,000.
00:24:10	S3	[inaudible 00:24:10]?
00:24:12	S1	AC plus 1 fault.
00:24:14	S3	I don't have my screen. Do you have control?
00:24:17	S1	I have control. Autopilot (Speaks in Foreign Language).

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

00:24:23	S3	English, English please.
00:24:24	S1	Okay. Autopilot is flying; we are still in the climb and the left turn, turning-wise no problems, so if you agree I would suggest ECAM actions.
00:24:37	S3	ECAM actions? And from? I cannot activate the checklist, [inaudible 00:24:41]. Thank you very much.
00:24:45	S1	You're welcome.
00:24:47	S3	AC plus 1 fault, lower override, Generator 1 off.
00:24:56	S1	I've lost the **nose** of the airplane right now.
00:24:59	S3	Okay. That happens from time to time, sorry for this.
00:25:01	S1	Okay.
00:25:02	S3	Generator 1, on. Is generator 1 recovered, yes or no?
00:25:09	S1	Just a second, it goes a little bit quickly. Okay. Lower is override.
00:25:17	S3	Lower?
00:25:18	S1	It doesn't show that on here.
00:25:20	S3	No? That's right, generator 1 is not recovered, everything is (Overlapping Conversation) so make it no, okay?
00:25:27	S1	Generator 1 recovered, I agree.
00:25:29	S3	Okay. Generator 1 off. FAK2 off. FAK2 on. Autopilot is off [inaudible 00:25:43].
00:25:45	S1	Yes, try again.
00:25:47	S3	Yeah, the FAK2 is off, is that FAK, that's for autopilot.
00:25:51	S1	So, we have…
00:25:52	S3	You have to fly manually, autopilot is off.
00:25:57	S1	Yeah, just a second. I'll try again.
00:26:00	S3	FAK2 is off, (Overlapping Conversation).
00:26:03	S1	Okay. Right now, is FAK2 off?

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

00:26:04	S3	Yeah, FAK2 is off so as long as it's off, it's not possible.
00:26:07	S1	I thought you put it back on with…
00:26:09	S3	No, no, no. Yeah, it's on but it's not working.
00:26:11	S1	I misunderstood. Okay.
00:26:13	S3	And is FAK2 recovered? It says it will be recovering right now, so FAK2 it says recovered, auto flight… keep autopilot off, keep it off. AC essential feet, alternate [inaudible 00:26:31]
00:26:32	S1	Okay.
00:26:34	S3	If this is successful, ATC transponder 2.
00:26:39	S1	Altitude is checked by…
00:26:40	S3	Now you can use your autopilot because the AC essential is working.
00:26:46	S1	Okay.
00:26:46	S3	Autopilot should now be possible.
00:26:48	S1	Okay. I'll try again.
00:26:50	S3	Yes. That's looking very good.
00:26:57	S1	Autopilot. Or autopilot 2.
00:27:00	S3	Of course. AC plus 1 ECAM action is completed, 11 of 11.
00:27:05	S1	Okay.
00:27:06	S3	Clear ECAM?
00:27:08	S1	Clear ECAM.
00:27:11	S3	Mario, we have now autopilot on, (Overlapping Conversation).
00:27:14	S2	Lufthansa 1221, turn left heading **0910**.
00:27:18	S3	Lufthansa 1221, left turn heading **0910**. And I would like to take control again.
00:27:26	S1	Okay, you have control.
00:27:27	S3	Okay? I have control and you continue please with the **system page**.
00:27:32	S1	Say again the last part.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

00:27:33	S3	Please continue now with the procedure flow, we are next to the system page.
00:27:38	S2	Okay. So, the elec system generator 1 is on, the generator 2 is still working, I suggest to start the **APU,** just as a backup.
00:27:46	S3	Very good idea. Perfect. Okay. But the generator 1 will be staying off, right?
00:27:53	S2	Yeah. Yeah.
00:27:53	S3	Very good. Very good idea. Okay. Clear elec?
00:27:58	S1	Clear elec.
00:27:59	S3	Clear elec. And continue with the inop systems and limitations.
00:28:04	S1	So we have landing limitations, inoperative systems limitations, hydraulic flaps slow, slats slow.
00:28:15	S3	And that's logical. Okay.
00:28:16	S1	Yeah. Then we do have [inaudible 00:28:19] 1 and spoilers 3 which causes a landing distance calculation.
00:28:26	S3	Okay. So, we need a new landing distance calculation?
00:28:28	S1	Nose wheel steering in crosswind, expect lateral control problem.
00:28:34	S3	Do we have crosswind?
00:28:36	S1	Yes, we do have crosswind, yes.
00:28:37	S3	So, we have lateral control problems.
00:28:39	S1	We will have some, yes.
00:28:40	S3	Okay. We have to think on it, okay?
00:28:41	S1	I agree.
00:28:43	S3	Okay?
00:28:45	S1	So, then we have the left windshield heat, the left window heat, and icy conditions, right PF only.
00:28:57	S3	Yeah. We have to think about it.
00:29:00	S1	Yeah, right.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

00:29:00	S3	What if there's no ice?
00:29:02	S1	With right PF it means, what, the right-hand seated PF or…?
00:29:08	S3	It's the right pilot flying must be on the right-hand side, if it turns icy. If it's icy.
00:29:12	S1	Okay, I get it. Okay, I understood. Okay. So left tank pump 1, right-hand tank pump 1 and blue elec pump.
00:29:26	S3	[inaudible 00:29:26] overflow and [inaudible 00:29:28], yeah? Okay.
00:29:33	S1	So, we have the blue elec pump, RA1, FAK1, generator 1.
00:29:38	S3	Yeah. Okay.
00:29:40	S1	And CAT III is also inoperative so which means CAT II only.
00:29:44	S3	CAT II only. I remember [inaudible 00:29:46]. It shouldn't bother us.
00:29:49	S1	Yeah, [inaudible 00:29:49].
00:29:51	S3	Good. So that is completed and now just leave as it is, (Overlapping Conversation) it over you. And please check that after [inaudible 00:30:00] procedure for our AC plus 1 fault, and make a quick read through and tell me especially if there are any non-indicated **items** that might be endangering our flight.
00:30:16	S1	Okay.
00:30:16	S3	Okay? Thank you.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

Appendix B MATLAB CODE FOR HEATMAPS

```
% load Pilot6rawdata.mat

realTime = num(:,1);
simTime = num(:,2);
planeNo = num(:,3);

% find where simTime starts  (use threshold of -0.5 sec to find last
large negative step)
inds = find(diff(simTime)<-0.5);
lastStep = inds(end);

% cut down data to start at last negative step in simTime
realTime = realTime(lastStep+1:end);
simTime = simTime(lastStep+1:end);
planeNo = planeNo(lastStep+1:end);

% take a section of the data and return heat for each planeNo
ind = simTime>7.254 & simTime<137.224;
time = simTime(ind);
rtime = realTime(ind);
plane = planeNo(ind);
[heat,heat0] = heat_time(rtime,plane);

% plot heat map on saved image
load CockpitImage.mat
figure
imshow(I)
hold on
sheat = sum(heat);
heat0 = heat0/sheat;
heat = heat/sheat;
sc = scatter([xIm;1065],[yIm;740],[heat;heat0]*5000,'r','filled');
set(sc,'markerfacealpha',0.6)


arrows = arrow_time(time,plane);
for i = 1:22
    for j = 1:22
        if arrows(i,j)>0
            arrow([xIm(i) yIm(i)],[xIm(j)
yIm(j)],'EdgeColor','r','FaceColor','g','tipangle',12,'width',arrows(i,j)
/10)
        end
    end
end
```


Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

Appendix C BENEFITS QUESTIONNAIRE

N	Question	Completely agree	Agree	Neither agree nor disagree	Disagree	Totally Disagree	Comments
1	You felt **confident** using the system, despite its novelty						
2	You would like to **use the new interface** in my daily activity						
3	The new interface is **intuitive** and **easy to use**						
4	The new interface presents the **information** in an **accurate way**						
5	The new system provides you with **the right information at the right time**						
6	The information provided by the system is **easy to read**						
7	The information provided by the system is **easy to interpret**						
	To answer the following questions, please compare the A320 cockpit currently in use with the enhanced interface just experienced						
8	The new interface is likely to effectively **support the monitoring task**						
9	The new interface is likely to effectively **support the piloting task**						
10	The new interface is likely to **reduce pilots' workload** in ***normal situations***						
11	The new interface is likely to **reduce pilots' workload** in ***unexpected/abnormal situations***						
12	The new interface is likely to **reduce the risk of distraction**						

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

13	The new interface is likely to **reduce the risk of tunnel attention**						
14	The new interface is likely to **reduce the likelihood of errors**						
15	The new interface is likely to better **support complex problem solving and decision making processes**						
16	The new interface is not likely to **affect your memory** on completed actions						
17	The pilots' **ability to anticipate or predict the future course of events** is likely to be better supported by the new system						
18	The way the information is presented in new interface is likely to **ease the collaboration between pilots**						
19	The *artificial landscape* provided by the primary flight display is likely to **improve your situation awareness**						
20	The new interface is likely to **raise and keep high your awareness on fuel**						
21	The **use of colours** is likely to promptly **direct your attention** towards the most relevant information						
22	The *touchscreen navigation display* **eases the browsing through flight details information**						
23	The *timeline/limitation tool* is likely to **raise consciousness of the flow of fly time**						
24	The *abnormal procedure checklist* is likely to **shorten the execution of ECAM procedures**						
25	The *abnormal procedure checklist* is likely to **improve the safety of operations by minimizing the likelihood of errors**						

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

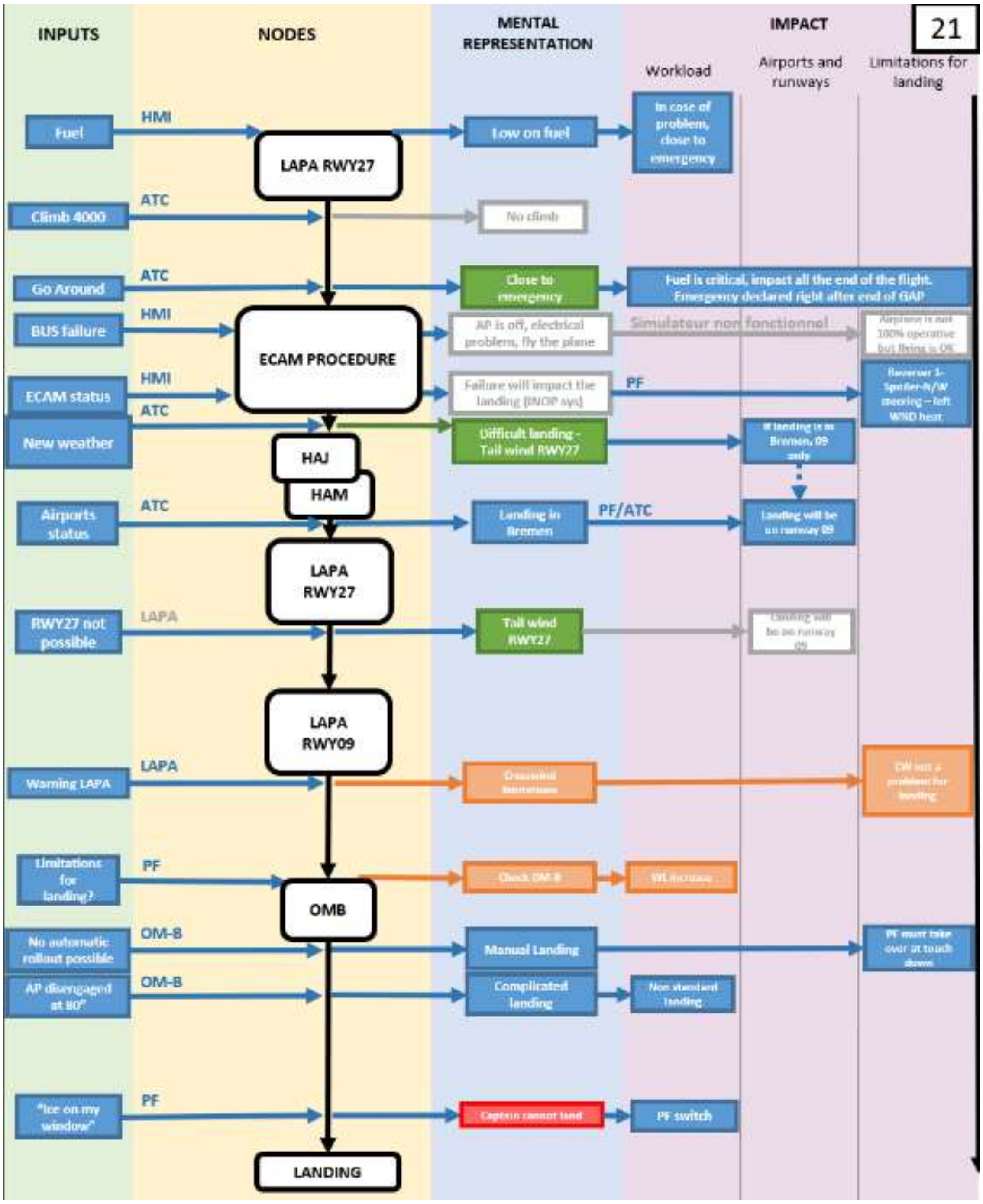
26	While using the *abnormal procedure checklist*, the indication of the number of overflow items is an information likely to **help in time management**.						
27	The *computerised abnormal procedure* (question Yes/No) gives a **better understanding** than existing procedure						
28	The *failure tree indication* **improves the situation** awareness of aircraft system failures.						
29	The **touch screen flaps** are easy to use						
30	The interface is likely to **better support the selection of alternate airports** in low fuel situations						
38	**Would you be happy to see this to happen automatically, or would you want it to be on request?**						

Please answer to the following open questions:

31	Is there any aspect from the new cockpit design that you'd like to see in your own cockpit?	
32	Was there anything you didn't like, or didn't find useful?	
33	Are there any other ideas for automation you could think of?	
34	Is there any particular part that you'd prefer to be mechanical (e.g. switches)?	
35	Do you think this advanced design is moving in a good direction?	
36	How comfortable would you feel in a completely digital (i.e. touch screen) cockpit? Rate from 1 to 10	
37	*[Optional – Adaptive automation]* When your workload is high and you are running out of time, is there something else that you would like the automation to do for you?	

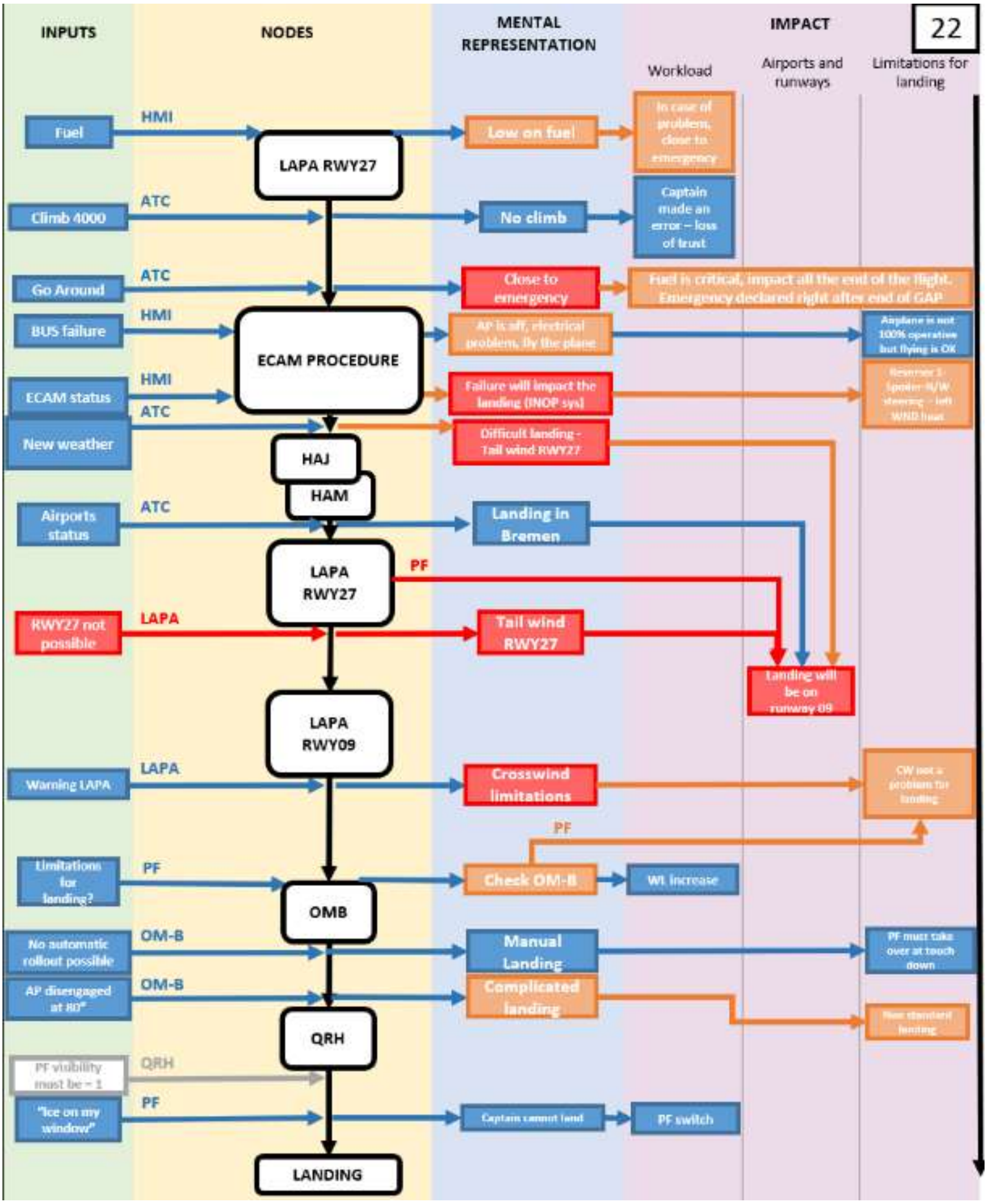
Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

Appendix D DESCRIPTION OF THE MERIA MODELS FOR EACH PILOT



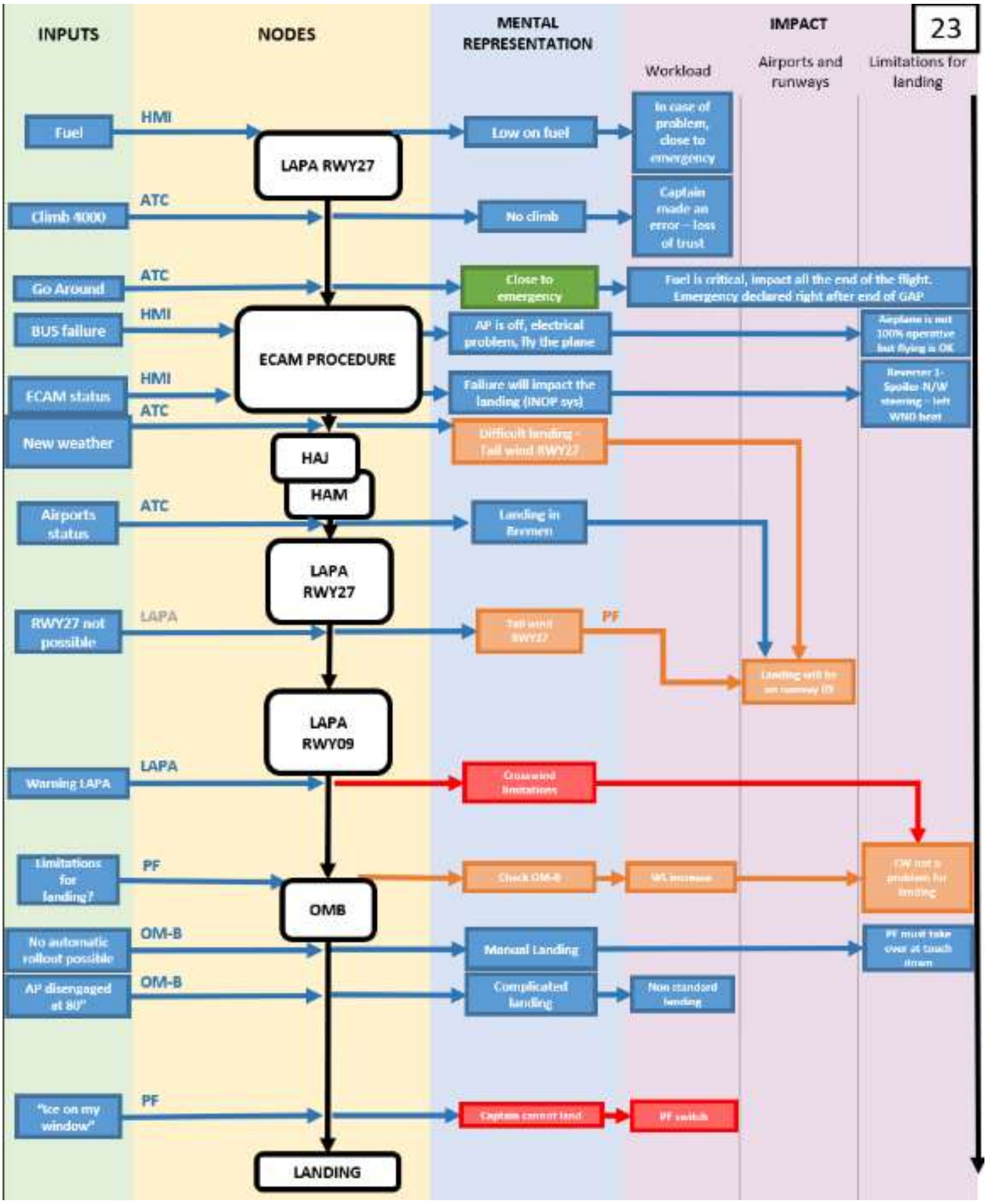
- The first officer understood pretty good the impact of some Inop Systems after the failure but didn't remember all of them.
- The co-pilot quickly understood the impact of the new weather on landing and initiated a discussion with the captain.
- First officer mentioned fuel quantity twice before discussing the declaration of Mayday situation with the captain at 1,1T fuel remaining.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.



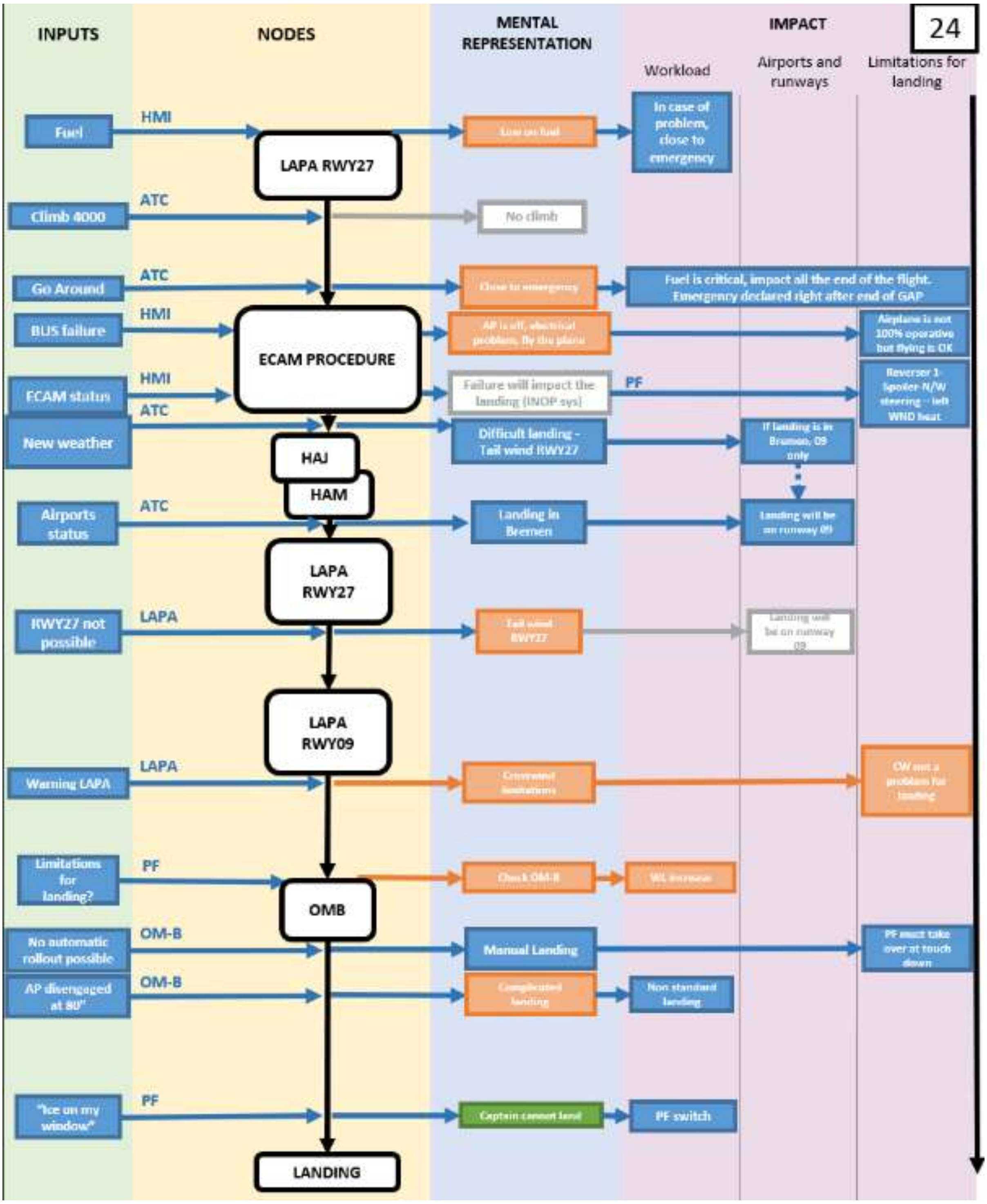
- The first officer had difficulty with the LAPA calculations and focused on them, which took time and therefore fuel.
- The co-pilot did not realize the impact of most of the Inop systems on the landing.
- First officer realized late that they were running out of fuel and only thought about landing as quickly as possible regardless of the conditions and risks involved. Which explains why "Landing in Bremen" is in blue and most of the items around it are orange or red.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.



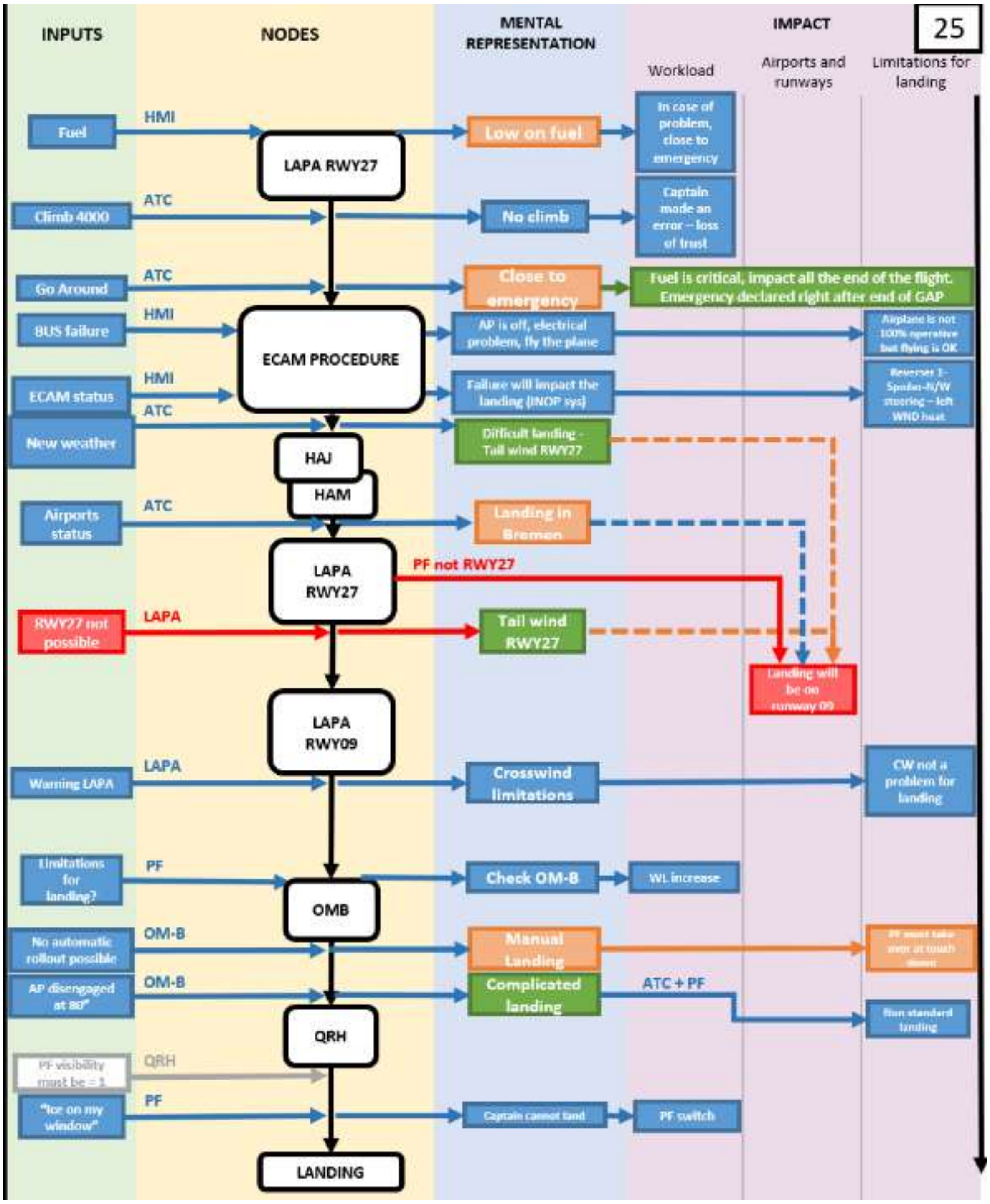
- The first officer noted that the fuel flow was quite high and that they were low on fuel and declared Mayday early in the scenario.
- The co-pilot did not consider the alternate airports but only Bremen Runway27 and tried to find solutions to shorten the landing distance.
- First officer did not fully realize that the new meteorological conditions combined with the state of the aircraft made the runway 27 landing impossible, although the impact of the inop systems was globally understood.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.



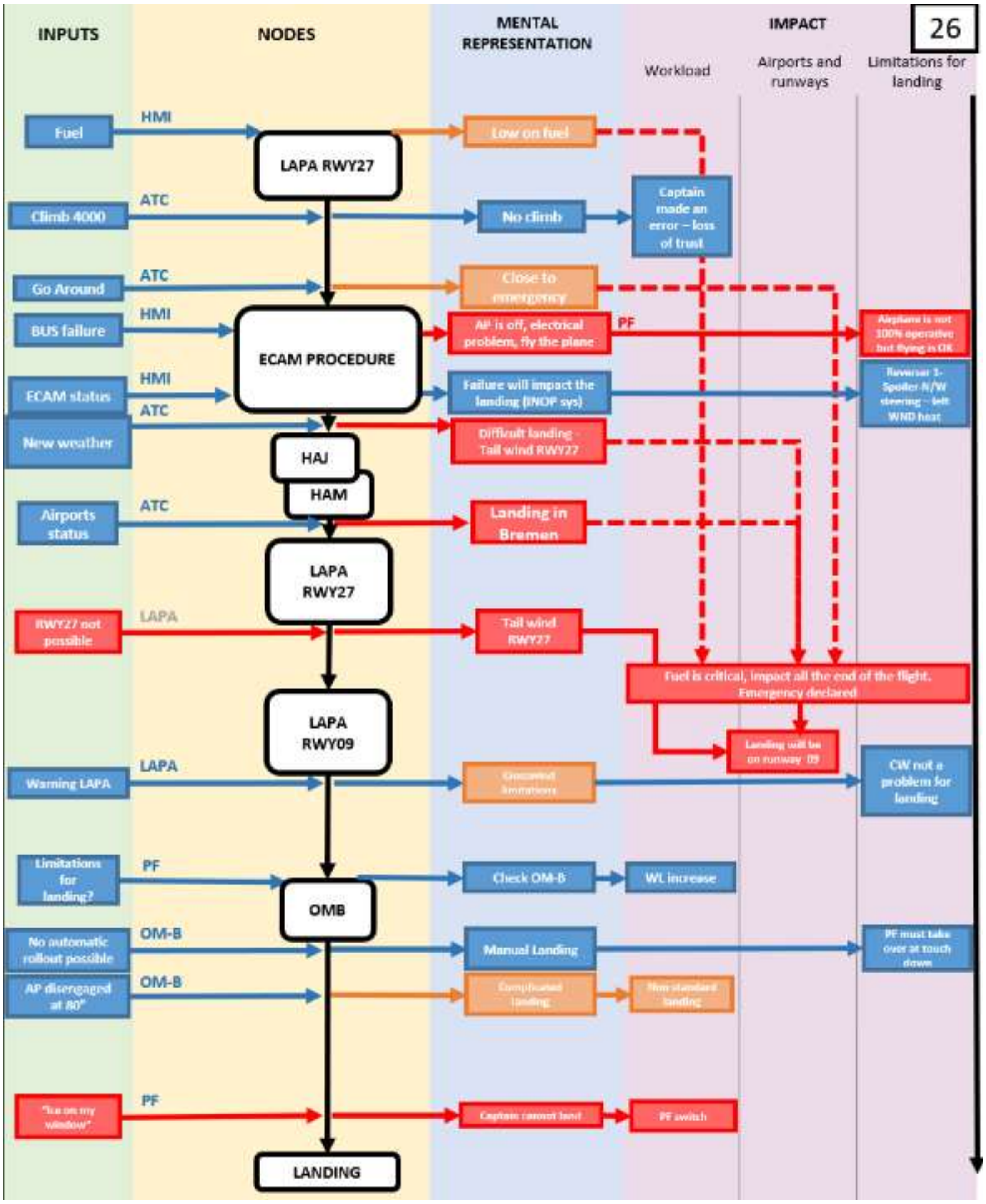
- The first officer proposed to start the APU to provide a second power source.
- For the second approach (RWY 09), after contacting the tower, the first officer indicated that they were low on fuel to ensure that the information was copied by ATC and prepared approach to save fuel.
- The first officer recalled that the captain's window heat and windshield heat were inoperative.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.



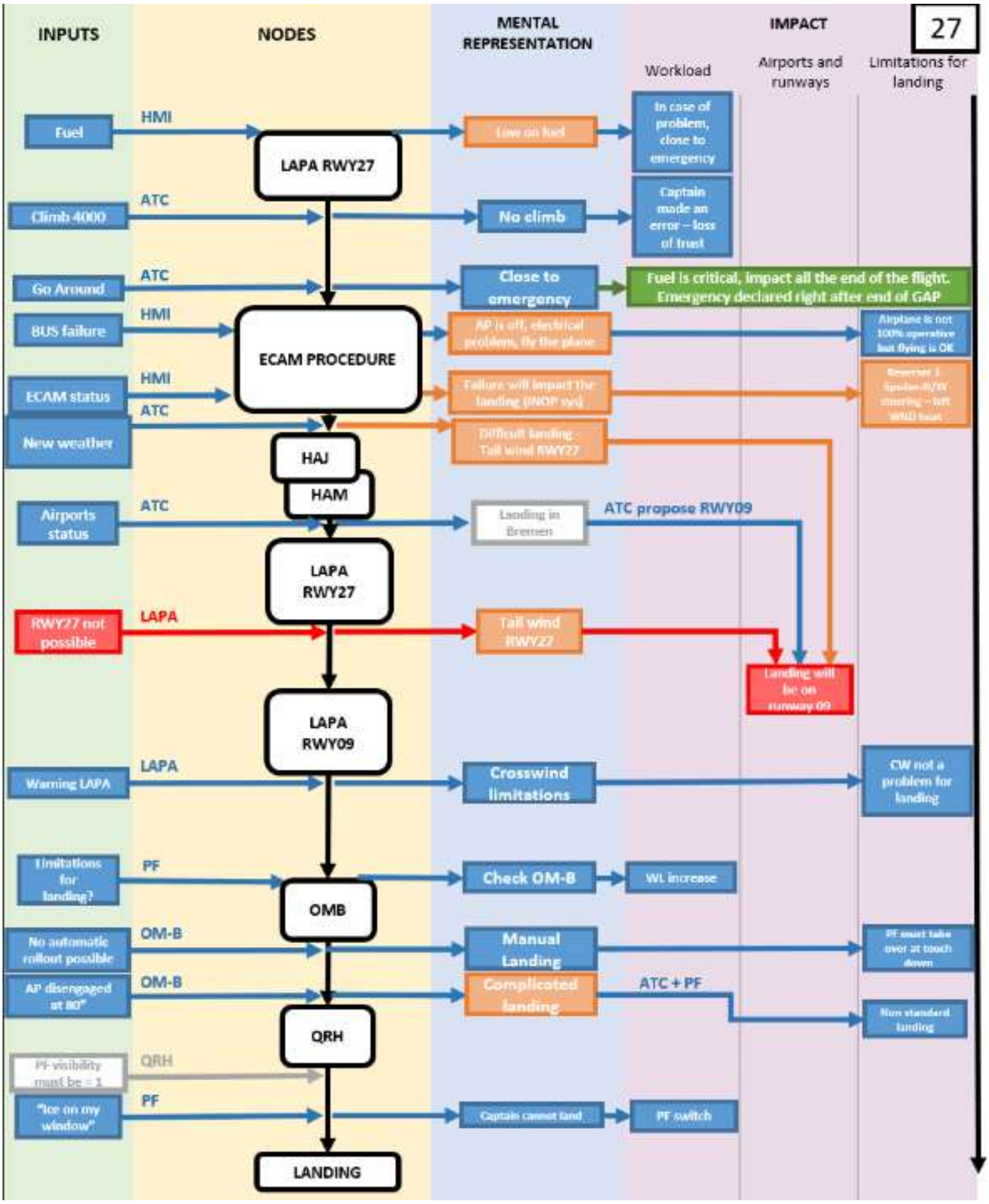
- The first officer identified the important inop syst especially for Bremen short RWY and, asked for latest wind information due to Nose Wheel Steering inop and the strong crosswind.
- With the new weather the co-pilot evaluated the alternate airports, requested to fly back to Bremen and proposed RWY 09. The captain asked to evaluate RWY 27 before.
- After checking the crosswind limitations the first officer confirmed that the manual rollout was possible and informed tower that they will stay on the RWY.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.



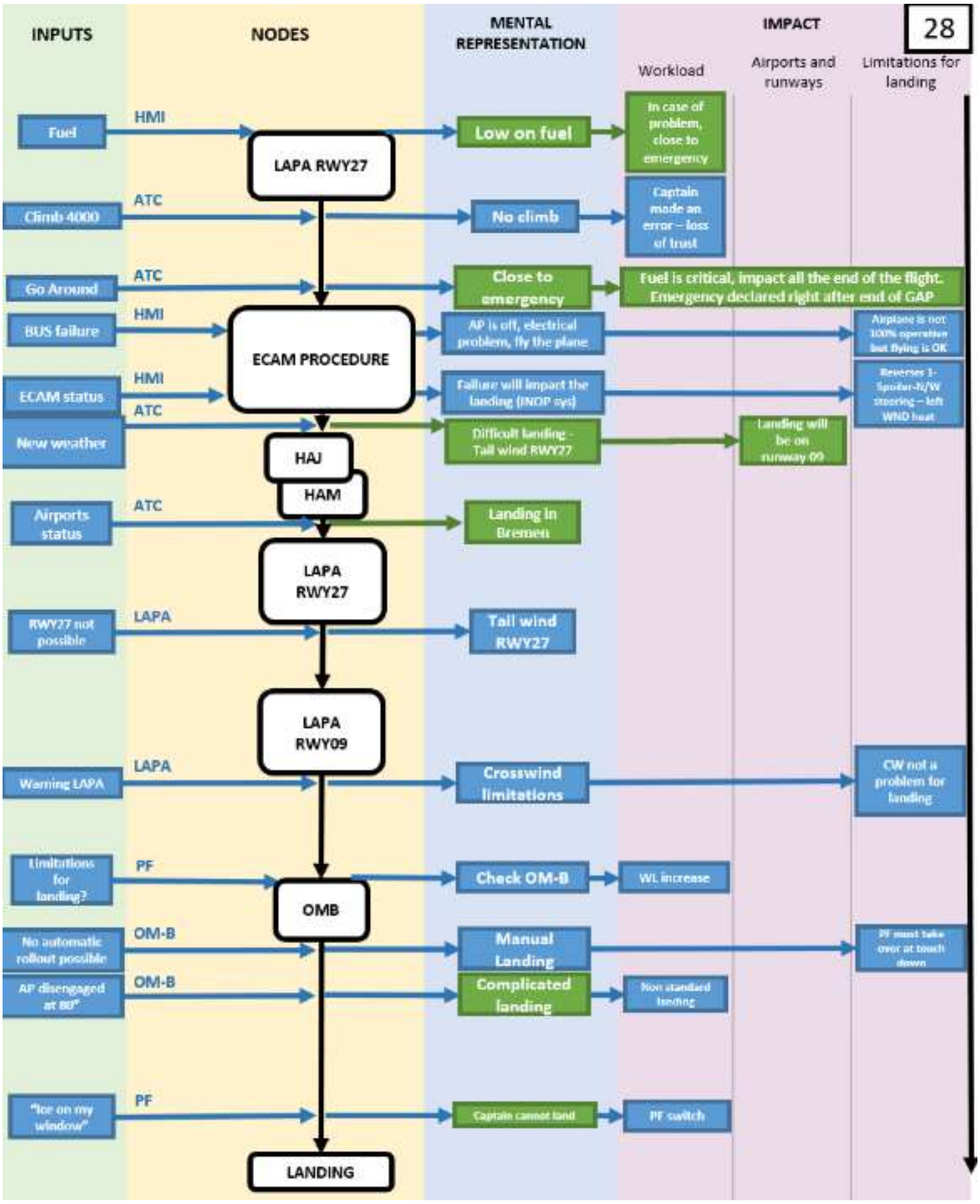
- The first officer requested alternate airports to ATC which were denied by ATC due to weather and inbound traffic.
- Just after realizing they were low on fuel the co-pilot wanted to declare emergency to Hamburg, to have priority over the inbound traffic.
- First officer understood the crosswind limitation in the OMB and that they've to do a manual rollout but didn't make the link with the nosewheel steering inop.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.



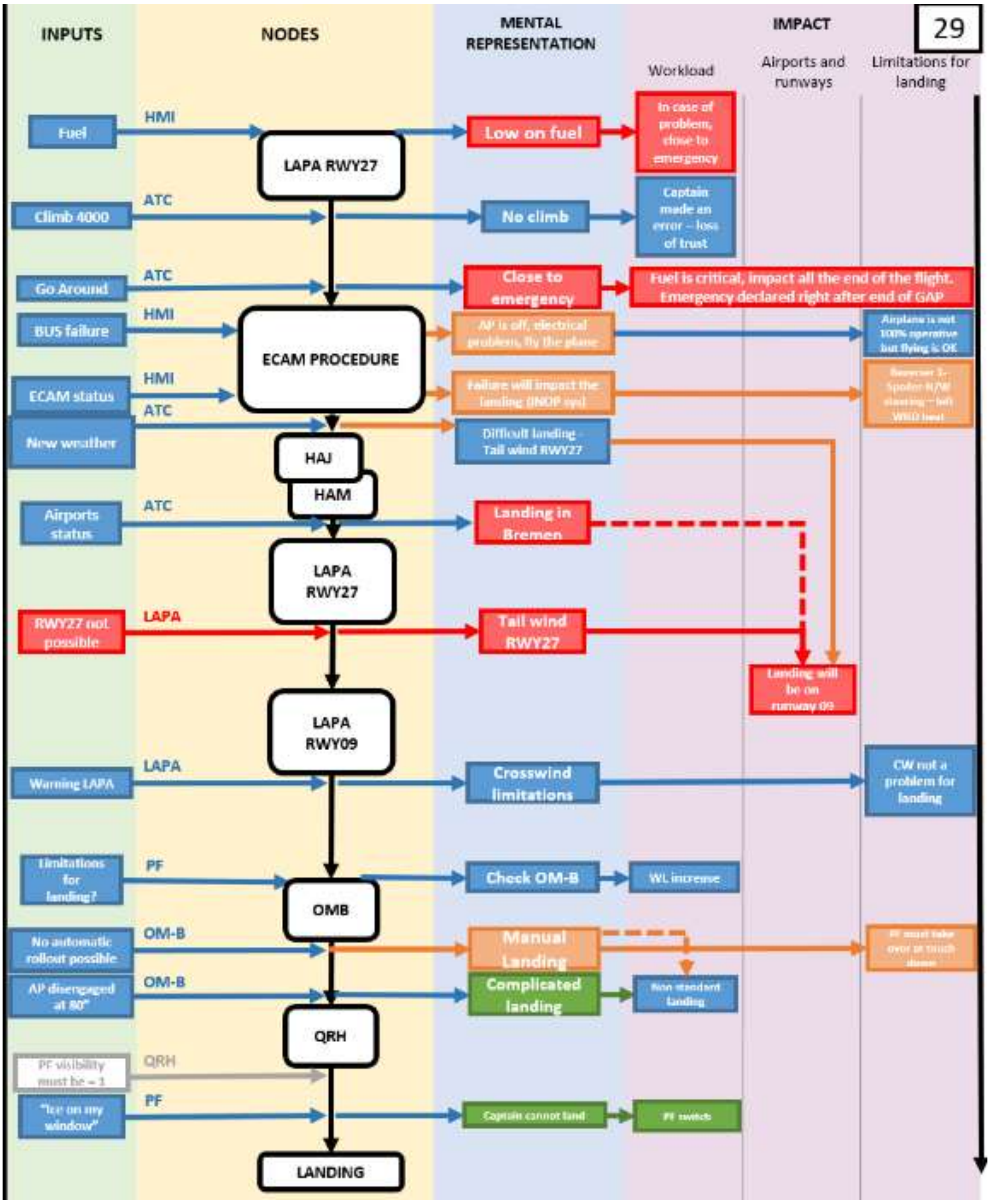
- The first officer declared Mayday after captain requests, but didn't give the reason of the emergency situation to ATC.
- The co-pilot proposed to take control with the RWY in sight, when the captain said that he had ice crystals on window.
- The first officer made three LAPA RWY 27 calculations for 2nd approach before captain asked for other options (alternates).

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.



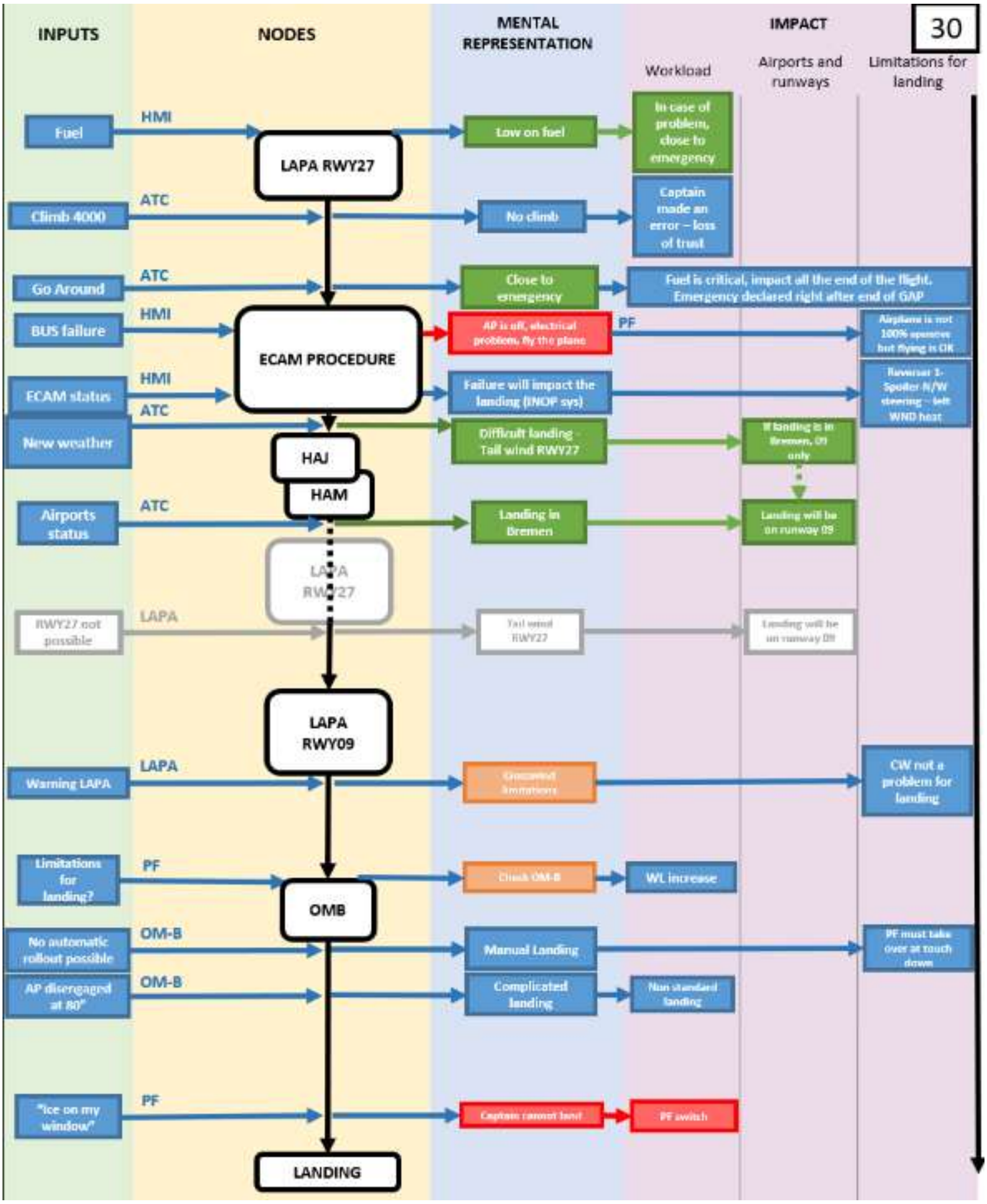
- The first officer identified the tail wind component with the new ATIS K. on RWY 27and therefore requested if RWY09 was available.
- The co-pilot looked for the alternates and decided to declare Mayday and informed ATC about the failure too.
- First officer remembered that one reverser was inop, ordered fire brigade and tow truck (Nose wheel steering inop) and verified that ATC were aware of the emergency situation a couple of time.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.



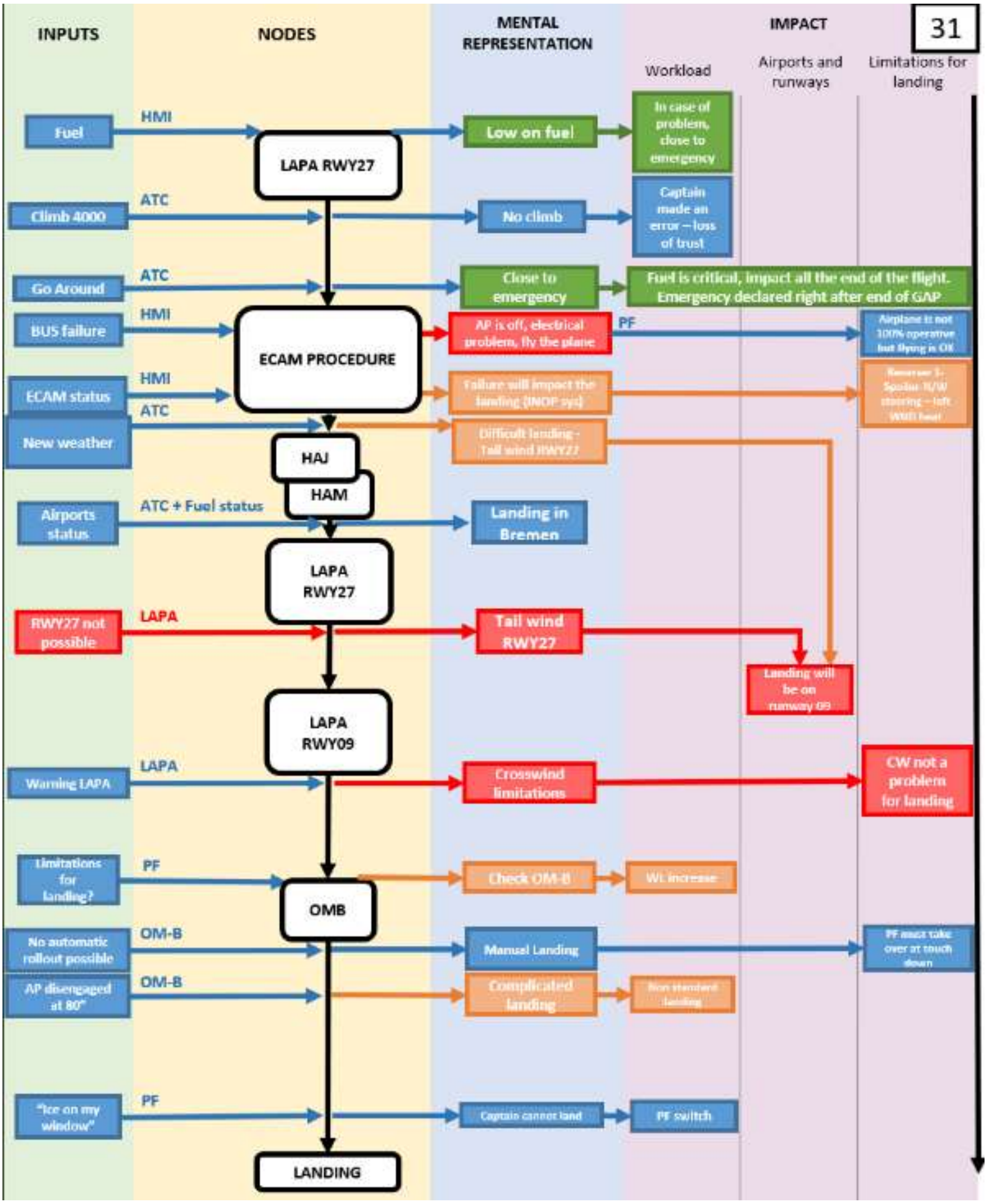
- The first officer noticed that the new wind would implicate tai wind on RWY 27 but didn't ask for RWY 09.
- The co-pilot identified that they were leaving the MSA (Minimum Sector Altitudes) providing at least 1000 ft obstacle clearance within 25 NM around Bremen knowing that the GPWS (Ground Proximity Warning System) was inoperative.
- After LAPA RWY 09's calculation the first officer requested full ground assistance, for after the landing.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.



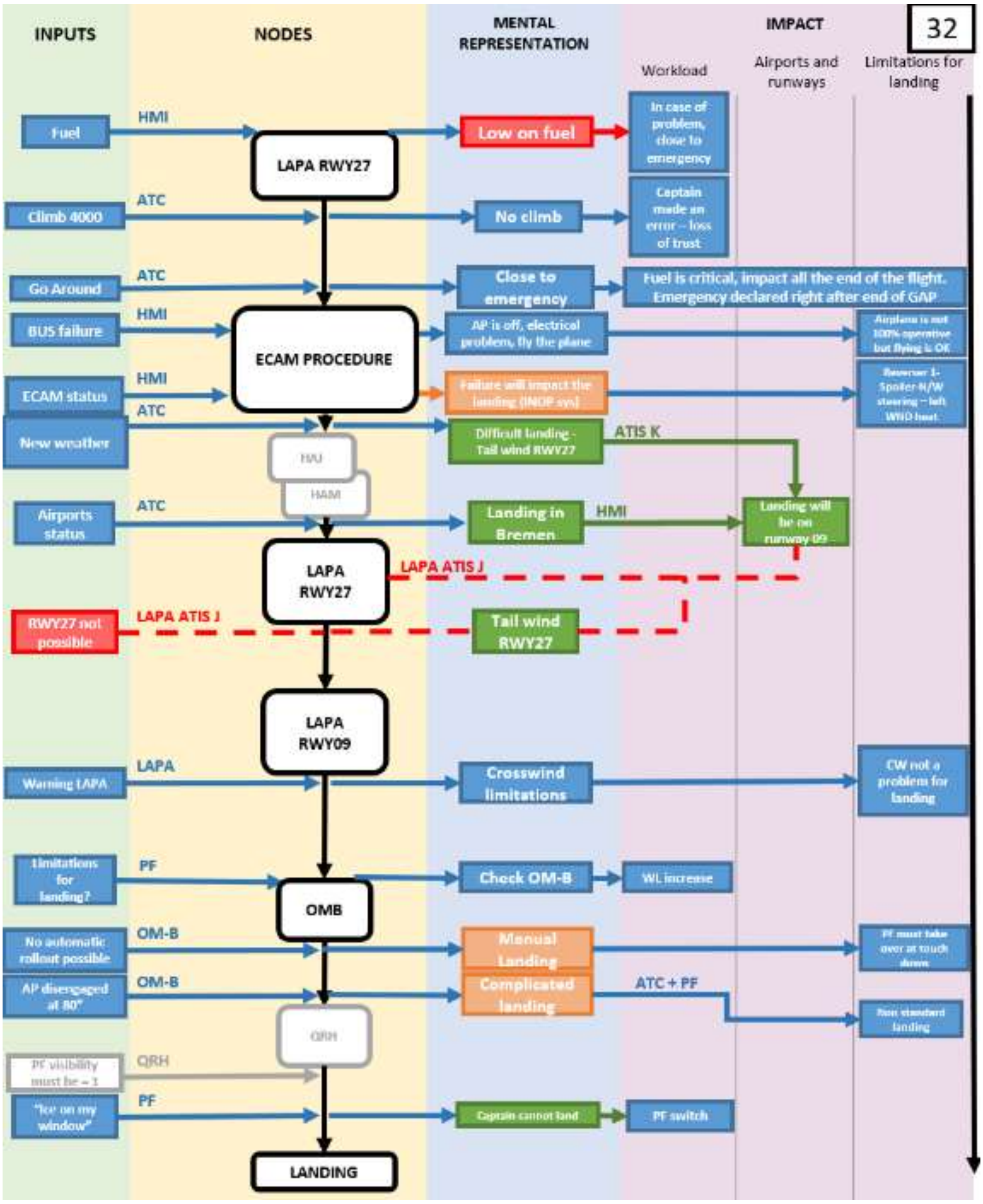
- The first officer noticed a few elements on PFD, like Ground Speed wasn't correct, the wind was the same as on ground, and the fuel was less than 2T.
- During the reading of the Inop Systems, the co-pilot immediately visualized their impact on the rest of the flight and for landing, except the window and windshield heat.
- The first officer noticed that they were flying away from Bremen, asked to fly back and RWY09 due to new weather conditions.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.



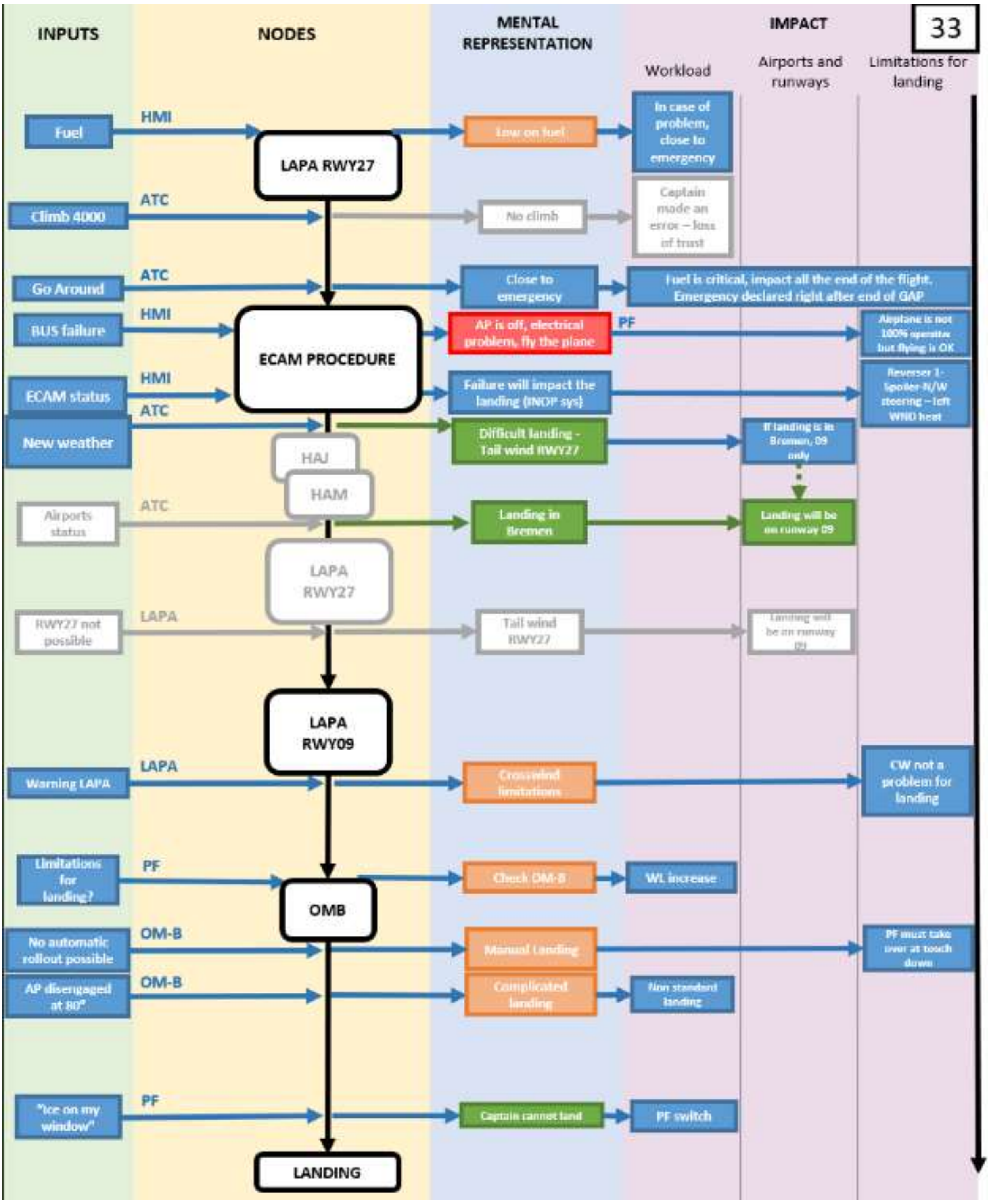
- The first officer saw very early that they had little fuel and projected himself onto a possible Go Around and no diversion possible.
- The co-pilot still requested alternate airports and remained stuck on the idea of landing on runway 27 despite the new weather conditions and AC state and the over-run possibility
- First officer made the link between the inop systems and the landing limitations.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.



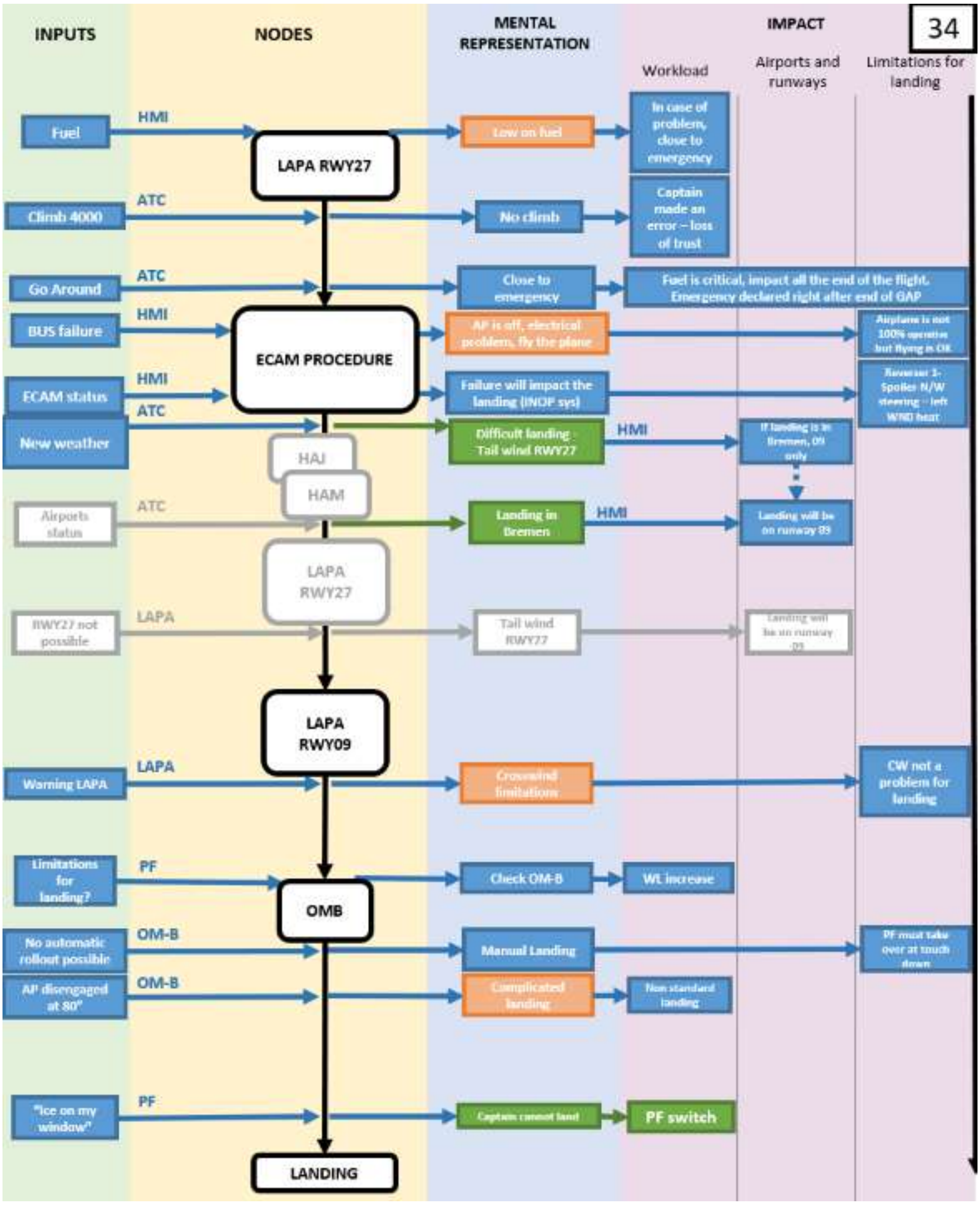
- The captain showed the first officer that the orange circle (30 minutes remaining fuel) was small, and he (the co-pilot) decided to declare an emergency.
- With the new ATIS the co-pilot proposed RWY09 and confirmed their choice by checking in the HMI the runways available in Bremen.
- The first officer did not make the link between the inop nose wheel steering and the manual rollout and, at 800ft above ground just before landing, realized that the Reverser 1 was inop but remembered window and windshield heats were inop.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.



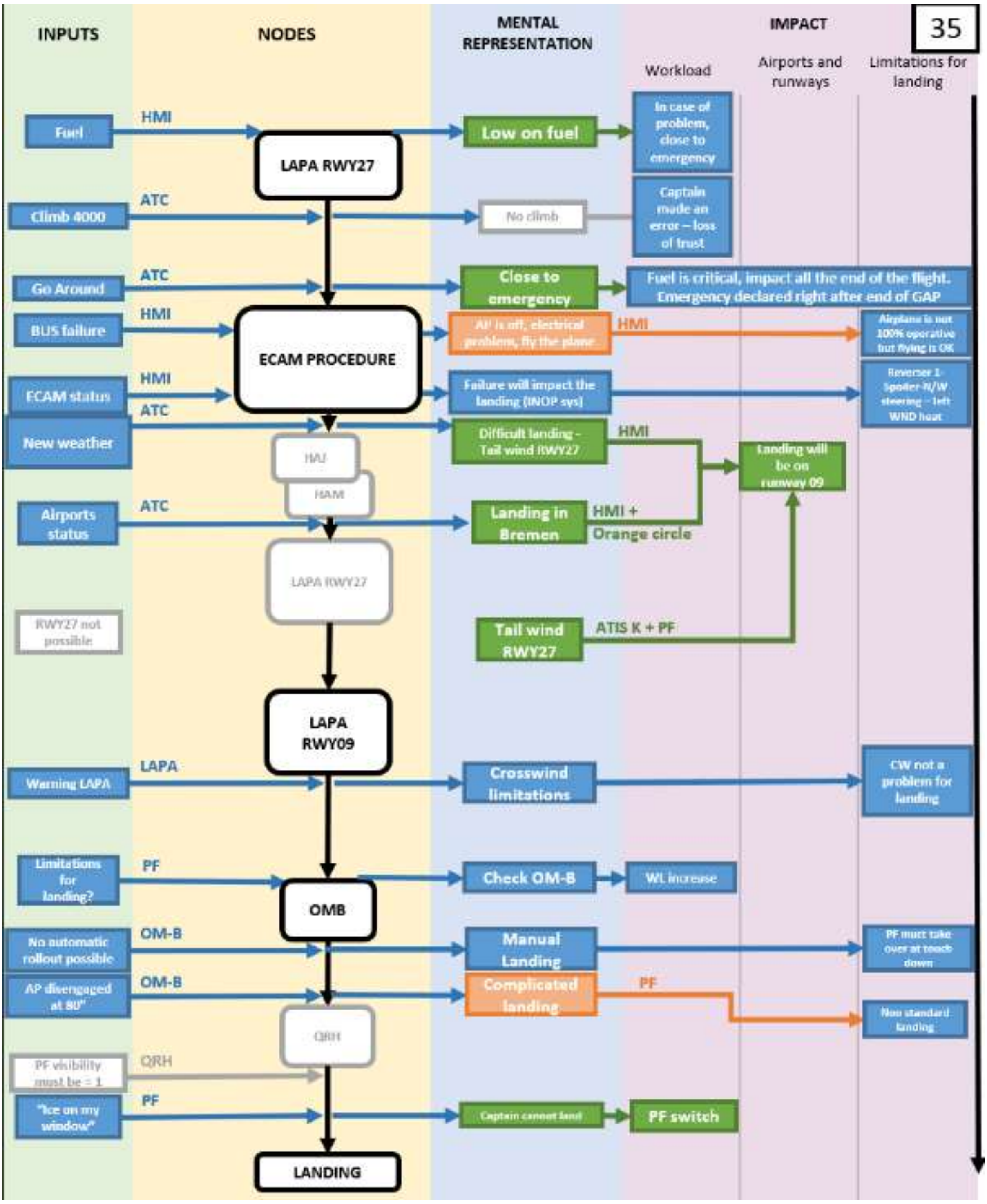
- The first officer noticed the fuel quantity after checking the orange circle HMI.
- The co-pilot read the inop systems and their impacts and understood right away that the captain would not be able to do the landing.
- First officer checked the RWYs availabilities in Bremen and then saw that the alternate airports were outside the circle and thus eliminates them from direct possibilities.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.



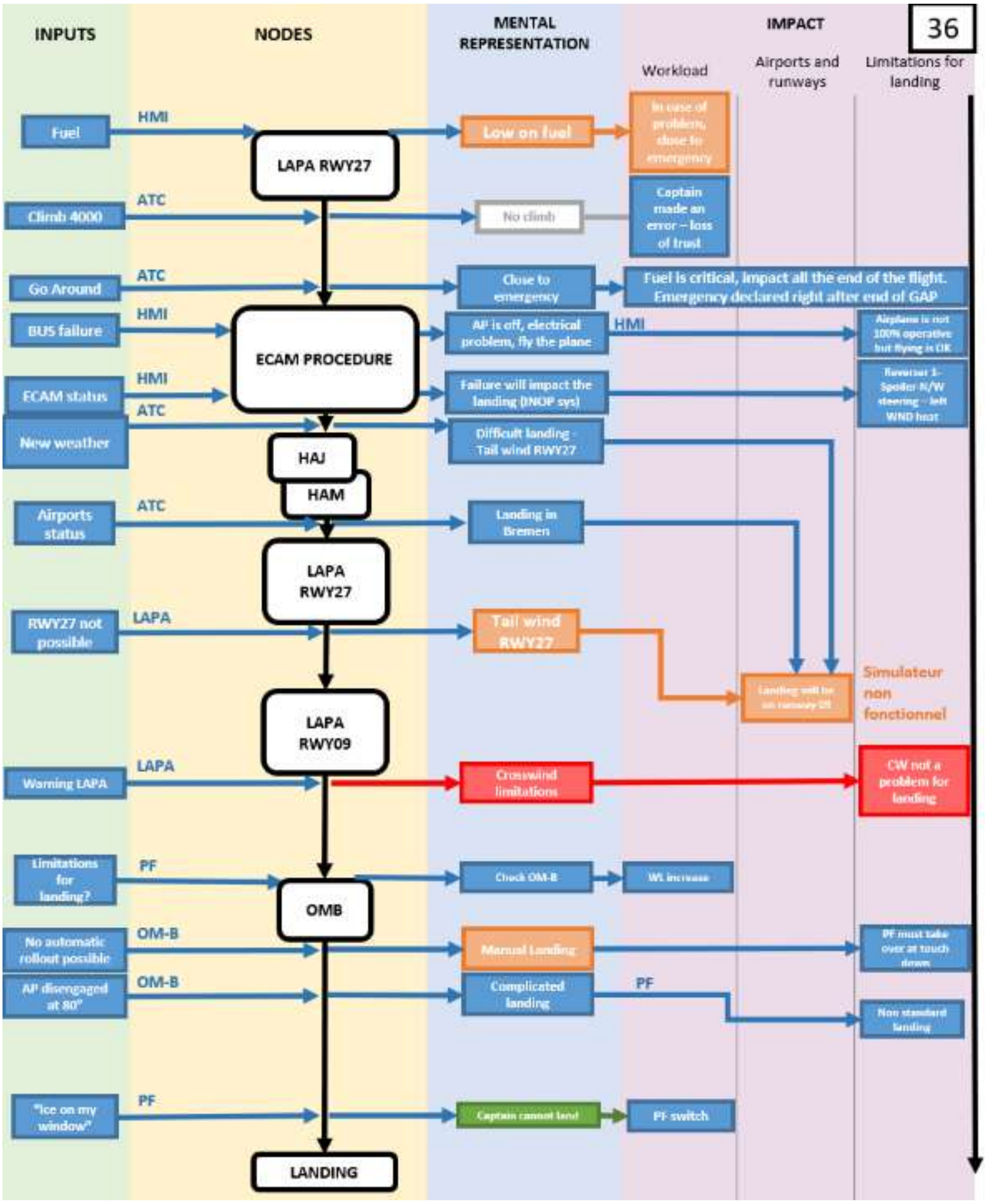
- The first officer read aloud the inop systems and their impacts for landing. The information in OMB "Fuel consumption increased" made the first officer look at the fuel quantity on PFD.
- The captain asked for any further options, that made the co-pilot look on Navigation Display and use the orange circle (30min fuel remaining) and therefore declared Mayday.
- The first officer declared Mayday for the electrical problem, asked for RWY09. After ATC gave Heading 260, co-pilot informed about fuel 30min remaining.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

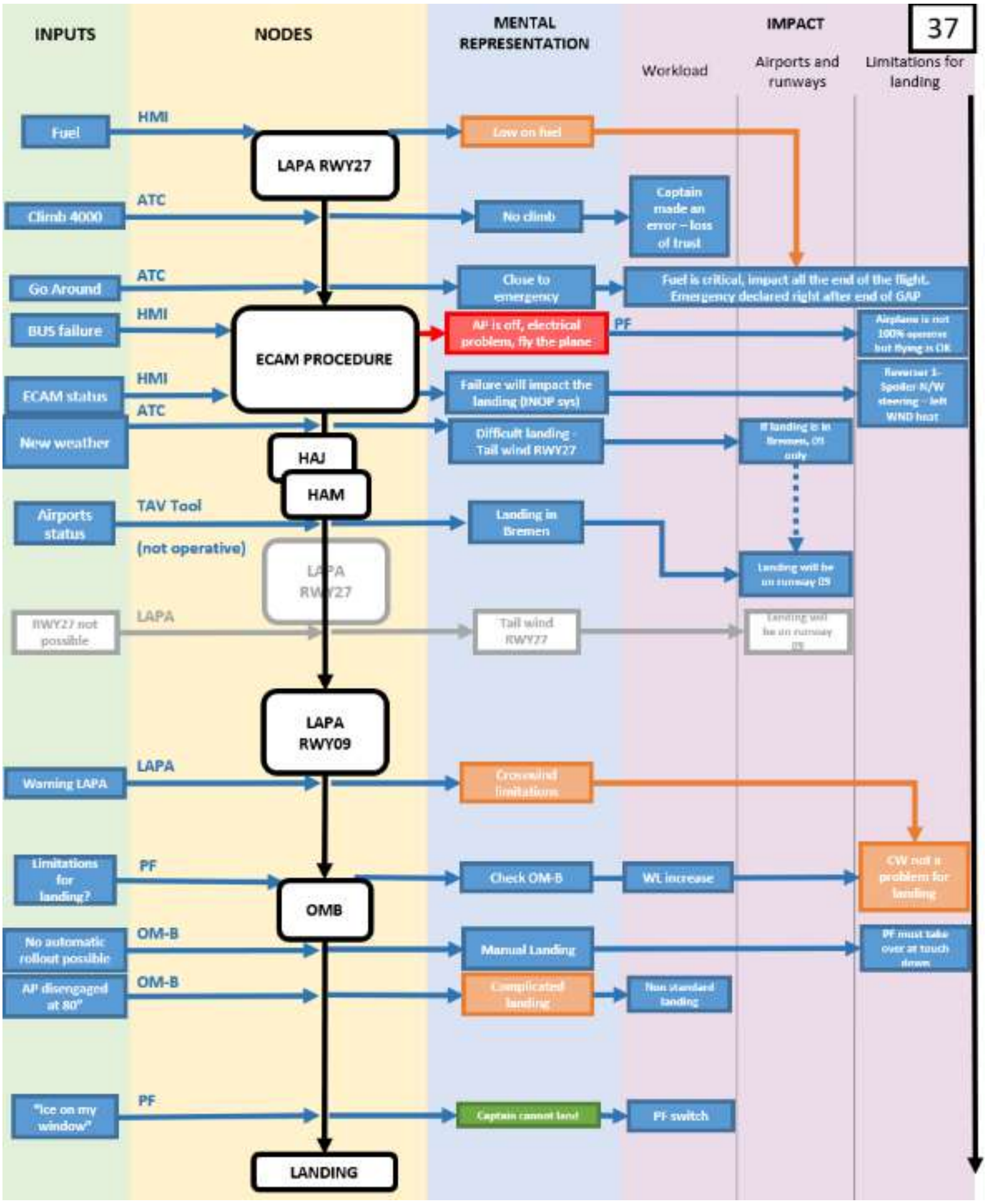


- The first officer saw the amount of fuel early in the scenario.
- The co-pilot noticed that the alternate airports were outside the orange circle and made the decision to declare Mayday.
- Thanks to the new interfaces, first officer saw very quickly that only runway 09 was available for landing.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

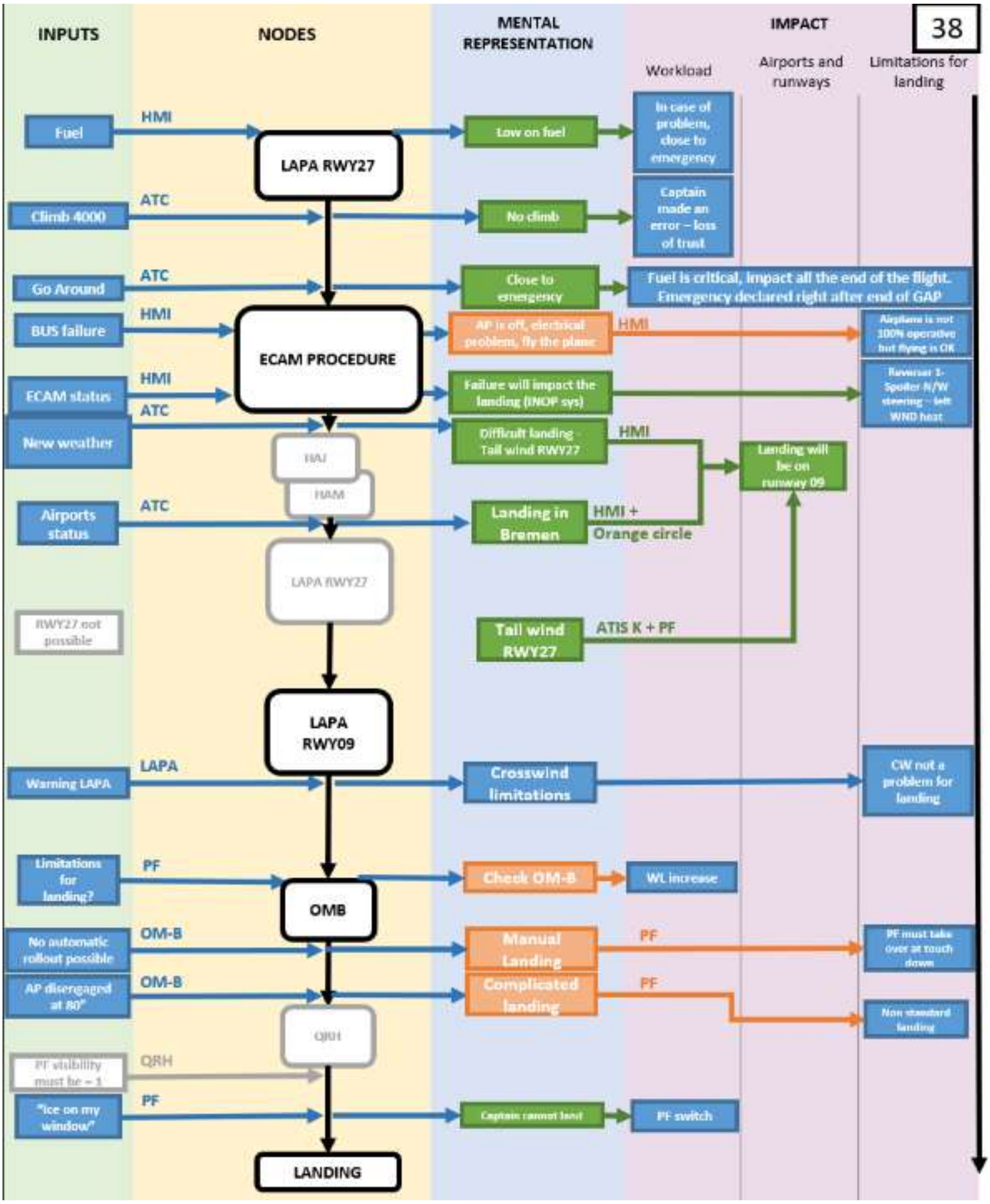


- The first officer evaluated the options with the orange circle (30min fuel remaining) and decided therefore to land in Bremen
- The co-pilot declared Mayday with 30min of fuel remaining because it's a rule (Final Reserve Fuel Mayday Rule).
- Due to a simulator malfunction, the first officer did not understand why the HMI showed that the RWY27 was available, although the LAPA calculation indicated otherwise.



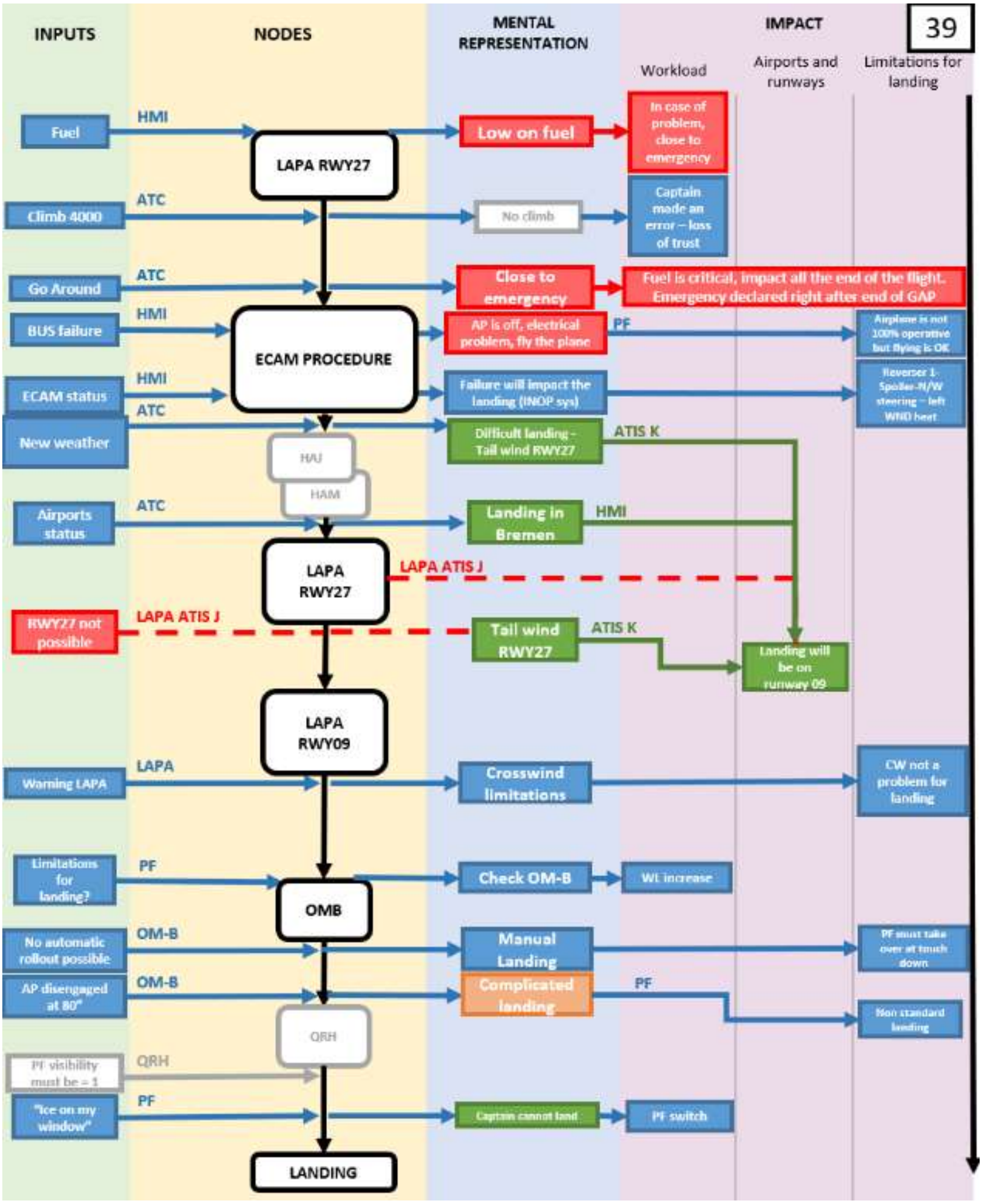
- After the failure, the first officer checked the RWYs available in Bremen, Hamburg, Hanover and, once again in Bremen and chose RWY 09 thanks to the HMIs.
- The co-pilot understood pretty good that they could perform an Autoland and disconnect the Auto Pilot and do a Manual Rollout.
- The first officer took control during last approach, on final, at the captain's request and, tried to perform a manual landing.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.



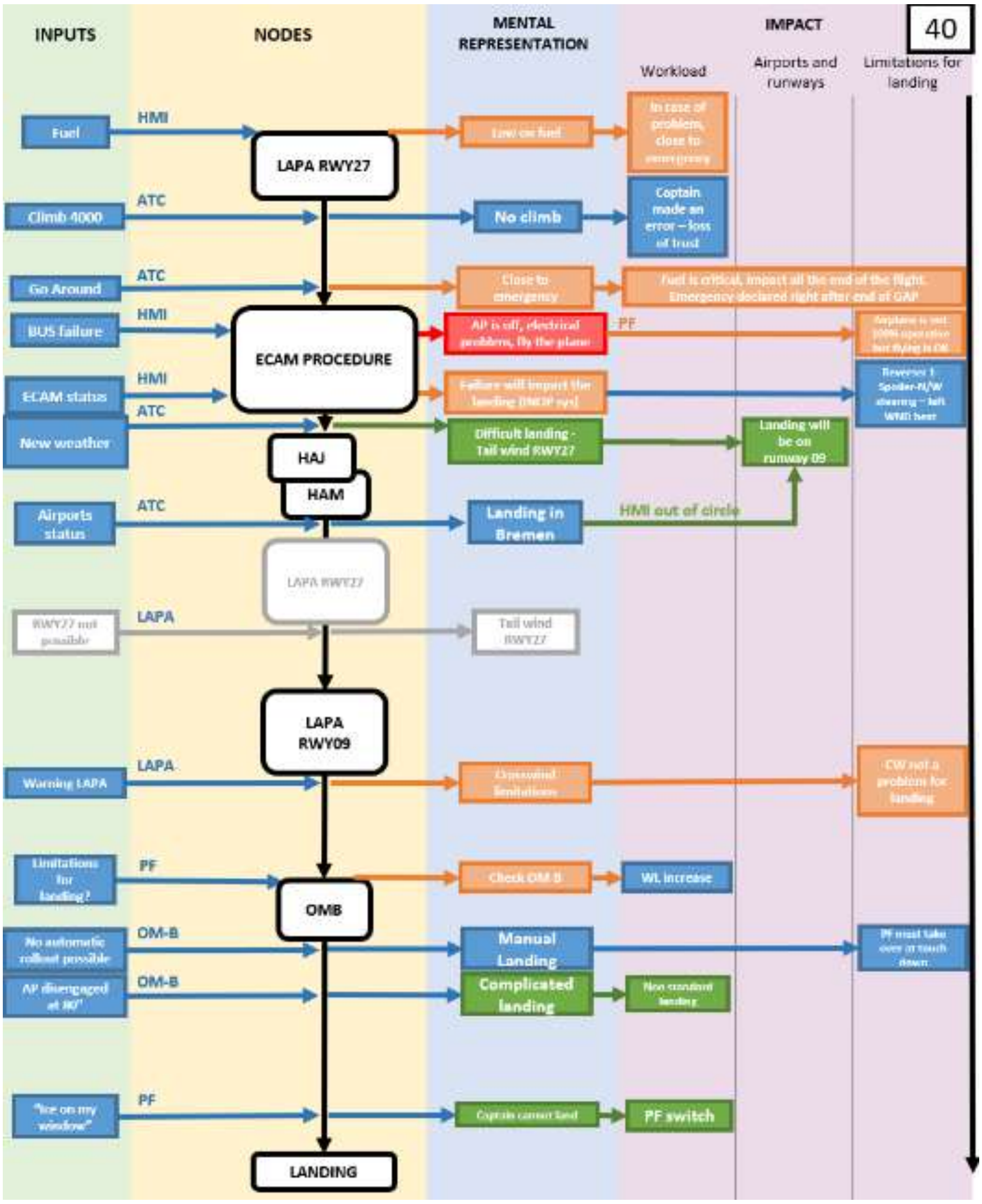
- The first officer noticed fuel before the first approach, mentioned it during GA.
- The co-pilot decided pretty fast after GA to land on RWY 09 in Bremen thanks the HMI and, decided to declare Mayday and failure with 33min fuel remaining. The LAPA calculation for RWY27 made the co-pilot understand why only RWY 09 was available.
- The first officer found nice the indications in the inop systems "Nose wheelsteering, In crosswind expect lateral control problem" but didn't make the link later with the manual rollout.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.



- The first officer saw that they were low on fuel when captain showed the gauge on PFD.
- The co-pilot understood that runway 09 should be used when reading the new weather report.
- First officer checked alternate airports avaibility through HMI and not by asking ATC.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.



- The first officer started the APU after the failure as backup generator, to keep redundancy.
- Due to weather conditions, the co-pilot asked at the beginning of the scenario to look for alternate airports.
- The first officer referred three times to the orange circle (30 minutes of fuel remaining) and, seeing no easy options, decided to declare Mayday.
- The co-pilot remembered from a previous simulator training that Airbus' actual ability, after an AC BUS 1 failure, is CAT I, which would have made landing not possible.
- The first officer proposed to the captain to land a little on the left of the RWY due to crosswind and one reverser inop.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.