A Novel Automated Electronic Checklist

Master of Science Thesis

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by

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Preface

Ironically, the first steps of this thesis have been set through a video call with Clark, discussing potential research topics. Long before Google saw the search frequency for the word pandemic skyrocket. During this perhaps *foreshadowing* meeting, Clark recommended a topic proposed by one of Control & Simulation's PhD students, something with emergencies and checklists... Soon, within a couple of days, Clark, Jelmer, and I agreed upon the research topic in a face-to-face meeting. And so the journey commenced, which was swiftly joined by first Max and later on Rene.

In the writing of this thesis, I am profoundly indebted to the Control & Simulation department and the many people involved with the research.
First of all, I would like to express my gratitude to Max, who is a stellar example of how much the staff actively and excitingly supports its students. Thank you for all your input and dedication, which for me was truly a motivating factor. Rene, I want to thank you specifically for your insights and input on the experiment design, the results analysis, and the writing of the paper.
I want to express my special gratitude to Clark, for your invaluable suggestions, insights, and contributions during our many *many* extensive and joyful meetings and brainstorm sessions that formed the foundation of this thesis. My appreciation also extends to Olaf S., Harold, Ferdinand, Andries, and Olaf G., without whom it would have been impossible to setup the experiment in record time, despite living in such difficult times.
Finally, I owe a singular debt to Jelmer, the PhD student who came up with *something about emergencies and checklists*. I had the privilege to rely on you with all the day-to-day work during the design phase, the development of the software, and in drafting all the materials for this thesis and its preceding work. At no time, my endless questions and requests during the most inconvenient times – on weekends or late at night – were of any issue.
Many others have supported me in ways large and small. I hesitate to name them in fear of leaving someone out, but they include Carl, who delivered valuable input in the design and the scenario development, and the participating pilots, who with great enthusiasm took part in the experiment.

Finally, I will let my excitement of the final product be expressed by the participating pilots, who, once seated in the digital cockpit, suddenly appeared like a child in a candy store. Which in my opinion is the best possible recognition of our work. Thank you all for this enjoyable experience. I will build upon this for the rest of my career.

Coen
London, September 2020

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Nomenclature

AC	Alternating Current
AECL	Automated Electronic Checklist
AFFTC	Air Force Flight Test Center
AIME	Automation and Information Management Experiments
ANOVA	Analysis Of Variance
APU	Auxiliary Power Unit
ASRS	Aviation Safety Reporting System
AST	Astana
ATC	Air Traffic Control
BTB	Bus Tie Breaker
CARS	Crew Acceptance Rating Scale
CCD	Cursor Control Device
CHKL	Checklist
CSS	Cascading Style Sheets
CSV	Comma Separated Values
DC	Direct Current
DUT	Delft University of Technology
ECAM	Electronic Centralised Aircraft Monitor
ECL	Electronic Checklist
EFB	Electronic Flight Bag
EFIS	Electronic Flight Instrument System
EICAS	Engine-Indicating and Crew-Alerting System
FHD	Full High Definition
FMS	Flight Management System
GPS	Global Positioning System
GPWS	Ground Proximity Warning System
HTML	HyperText Markup Language
IDG	Integrated Drive Generator
ILS	Instrument Landing System
IRS	Inertial Reference System

JSON	JavaScript Object Notation
LOA	Level of Automation
LOC	LOCaliser
MC	Master Caution
MCAS	Manoeuvring Characteristics Augmentation System
MCP	Mode Control Panel
Mdn	Median
METAR	METeorological Aerodrome Reports
MP	Middle Panel
MPS	Multi Pilot Simulations BV
NASA	National Aeronautics and Space Administration
NAVAID	NAVigation AID
NC	Normal Checklist
ND	Navigation Display
NNC	Non-Normal Checklist
NOTAM	NOtice To AirMen
OVRD	Override
PAX	Passengers
PF	Pilot Flying
PFD	Primary Flight Display
PM	Pilot Monitoring
PNF	Pilot Non Flying
QRH	Quick Reference Handbook
RA	Radio Altimeter
RCO	Reduced Crew Operation
RNAV	aRea NAVigation
RSME	Rating Scale Mental Effort
SAP	System Annunciater Panel
SART	Situation Awareness Rating Technique
sECL	simplified Electronic Checklist
SIS	System Interactive Synoptic
SPO	Single Pilot Operation
TAF	Terminal Aerodrome Forecast
TCAS	Traffic Collision Avoidance System

TR	Transformer Rectifier
UAAA	Almaty
UAUU	Kostanay
UHD	Ultra High Definition
USTR	Roshchino
VREF	Reference Speed
XGA	eXtended Graphics Array

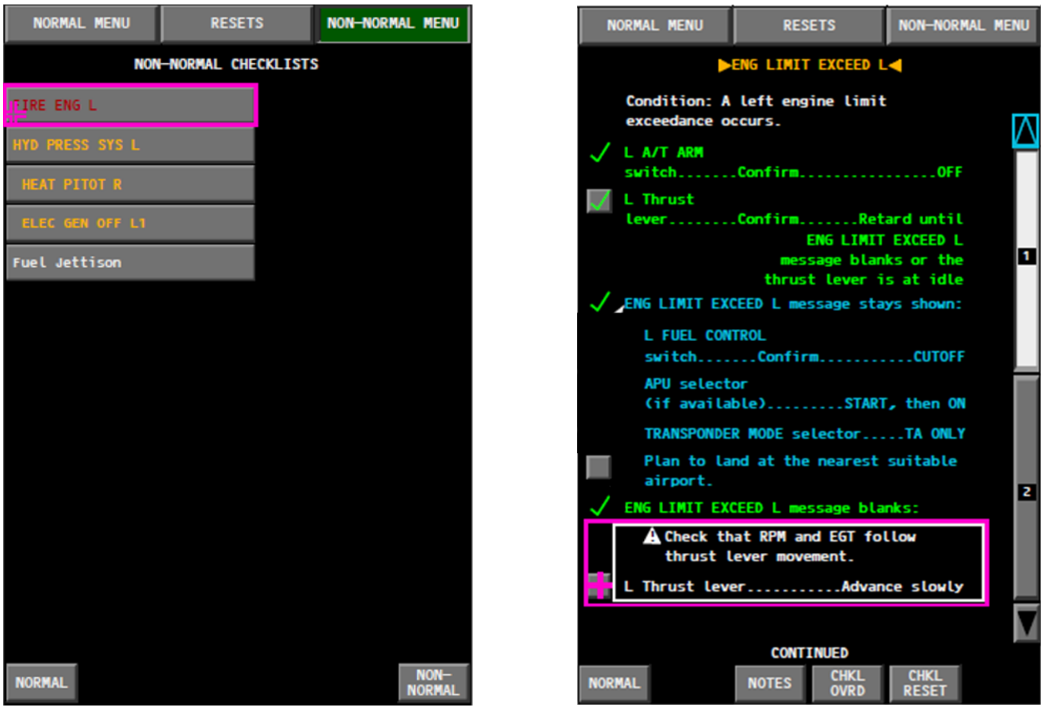
1
Introduction

The primary purpose of checklists is to ensure the aircraft is correctly configured for all stages of flight, including non-normal events [1]. They have become conventional on aircraft ever since a fatal crash of a Boeing B-17 in 1935 from which it became clear that aircraft functions and operations have become too complex for pilots to memorise to the full [2][3]. Two types of checklists are distinguished, Normal Checklists (NC)s and Non-Normal Checklists (NNC)s [4]. NNCs aim to correct, compensate, or otherwise accommodate for an experienced non-normal condition [4][5]. They are accessible through a Quick Reference Handbook (QRH), a hardcopy manual containing NCs and NNCs. However, QRH-use was prone to numerous issues [4][6], leading to the development of Electronic Checklists (ECL)s for the Boeing 777 which became certified in 1996 [4][7]. The ECL collaborates with the Engine Indication and Crew Alerting System (EICAS), which through messages indicates non-normal situations to the flight crew. Upon detection by EICAS, the associated NNC is immediately displayed on the ECL inside the non-normal menu (see Figure 1.1a), from which the individual NNC can be opened (see Figure 1.1b). Boeing families equipped with EICAS and ECL displays are the Boeing 777, Boeing 747-8, and the Boeing 787 (see Figure 1.1). The latest ECL development is the introduction of touchscreens for all forward flight displays on the Boeing 777X, in a push to stimulate work efficiency and intuitiveness. The Airbus electronic checklist derivative is part of the Electronic Centralised Aircraft Monitor (ECAM) system, where instead of allocating two separate displays (EICAS and ECL), an integrated approach on a single display was adopted with the difference that the pilot cannot choose on what checklists to execute. Hereinafter, the Boeing paradigm receives the main focus.

Notwithstanding the fruitful checklist evolution, human-induced checklist incidents, as reported by the Aviation Safety Reporting System (ASRS), still accumulated for 38% of selected cases for a period between March 2017 and March 2019 [9][1], highlighting room for improvement. Especially in light of the current trend towards Single Pilot Operations (SPO)s, where manufacturers such as Airbus, Boeing, and Embraer and US Congress [10] have publicly indicated an active attempt towards realising SPOs in order to match forecasted pilot shortages and estimated annual operating cost reductions of up to $15–60 billion [11][12].
However, making SPOs the new reality would require massive changes in current aircraft fleets, operations, public acceptance (for commercial flights specifically), and complying with regulatory bodies. In fact, it is by definition mandatory that all large commercial aircraft fly with no less than two pilots. Even so, any modern flight deck should already implicitly adopt SPO-like measures since regulations stipulate that aircraft must be operable by a single pilot from either seat, to address pilot incapacitation, impairment, or otherwise.

The inability for current aircraft to handle non-normal situations with a single pilot, being it for regulatory purposes or SPO adoptions, was exposed in a research by NASA [13–18]. In six non-normal events using a Boeing 737-8 level D certified simulator, participants indicated significantly higher experienced workload and lower perceived safety for the SPO condition when compared against a two-member crew. Especially for SPO runs, workload-shedding of tasks took place, wherein among others checklist usage was sacrificed to attend other more vital tasks [14]. Also, performance deteriorated. For example, in the rudder trim runaway failure, time for troubleshooting increased fivefold and poor diversion decisions compromised flight safety under the

[1]Based on a sample of 50 ASRS reports



(a) (b)

Figure 1.1: Non-normal checklist menu in **(a)** and an opened checklist in **(b)** as displayed on the Boeing 787 ECL [8]

SPO condition [18]. The research concludes with the statement that the technology is available, but rather its implication and the development of automation and user interfaces is the issue [13]. Non-normal events, in particular, form a bottleneck and ask for advancement.

A Non-Normal Checklist provides system and operational information to the pilot and step-by-step instructions to configure the flight deck in accordance with the failure, to contain, isolate deteriorating systems, to restore system functionality, and to avoid any hazardous situations. Many of the steps require the pilot to move switches and selectors, which in ECL-equipped aircraft are tied to sensors. The sensible checklist steps, or closed loop line items, allow the aircraft to check whether the step is complete [8]. Therefore, closed loop line items would make excellent automation candidates. Automating closed loop line items would alleviate the mental and physical effort required, and consequently free cognitive resources to be concentrated on resolving the non-normal event or on other urgent tasks. Additionally, no attention shifting between different panels is required, displayed checklists are shorter, and automation has the potential to complete such tasks faster than humans. Integrating automation in the process of checklist completion would allow the ECL to better attest to non-normal situation's time pressure, spikes in workload, stress, and problem-solving needs [19][20] and perhaps already set a next step towards realising SPOs.

Multiple recent studies have evaluated in one or more ways to adopt these notions. A study by Thomas [21] evaluated what level of automation was most appropriate to automate a set of checklist 'memory items'. The automation was augmented with voice messages to keep the pilot informed on what the automation is doing. Results indicated lower subjective workload with automation and the voice interface, however, the study did not consider any performance measures. Etherington et al. [22] explored a different avenue to enhance the ECL's NNCs. In a series of research, a combination between an enhanced synoptics display and a shortened ECL was developed to lower time requirements and provide a deeper and more intuitive understanding of an experienced failure. Average time savings between 25% and 30% were achieved over two scenarios, and the study indicated decreased experienced workloads. Finally, Li et al. [23] chose to integrate the ECL into EICAS, comparable to the functioning of ECAM, to enforce close spatial proximity [24]. Again time savings were found, but a more challenging comparison could have been made since the design was compared against a digital version of the QRH.

Objective The main objective of this thesis was to redesign the ECL in order for pilots to better address non-normal events. This thesis proposes automation to be applied on checklist execution to lower workload and time requirements. Automating checklist execution is an effort only considered by one other research found [21]. However, this study solely focused on memory items, did not thoroughly stress the pilot in the scenario tested, and did not evaluate variables such as time requirements, situation awareness, and decision-making. Additionally, this thesis proposes to reassess the location and timing of checklist information presentation, to reduce checklist size and show directly pertinent information only. This is done in order to achieve that the pilot will maintain situation awareness despite implementing the aforementioned automation. Comparable approaches have been explored in other research. For example, only showing the current step [23], similar to ECAM, or reducing checklist length by showing the information through synoptics [22]. However, no other studies found explored the removal of checklist steps presented to the pilot, as they have now become the automation's responsibility. Finally, none of the aforementioned studies assumed a touchscreen-based apparatus for their experiments.

Scope In order to evaluate the objective, the proposed design is compared against a reproduced Boeing 787 ECL in a human-in-the-loop experiment wherein 12 commercial pilots conducted two non-normal scenarios, an electrical and a hydraulic failure. In a between-subjects design, each participant was assigned one of the ECL displays (ECL or AECL) to conduct both scenarios and were evaluated in terms of time requirements, experienced workload, situation awareness, decision-making, managing a secondary task, and their design acceptance. Finally, potential automation drawbacks such as complacency [25–28], automation bias [29][30], and skill degradation [31][32] were not considered for this research.

Research Question To date, no comprehensive study was found that assumes automation as a viable approach in non-normal event resolution tasks with today's most state-of-the-art equipment. Therefore, the following research question will be addressed in this thesis.

> Research Question
>
> How does the proposed Automated ECL (AECL) design compare against the state-of-the-art ECL in terms of workload, time requirements, and situation awareness during non-normal events?

Thesis Outline Part I of this thesis presents the paper written, which covers the proposed AECL design, the conducted experiment, and the obtained results. In the second part of this thesis, the literature study is enclosed, which is subdivided into four chapters. The literature study begins with chapter 2, wherein checklists and the state-of-the-art Boeing 787 will be discussed in detail. Next, in chapter 3, more colour will be provided on the nature of non-normal events and how they limit current aviation developments towards a reduced flight crew. Thereafter, chapter 4 breaks down the concept of automation and highlights both is benefits and drawbacks. To complement the literature study, in chapter 5, a detailed review of situation awareness will be presented. Part III presents the AECL design in more detail and finally, in Part IV, the appendices are presented to provide additional insights in the preceding parts of this master thesis.

I

Article

A Novel Automated Electronic Checklist for Non-Normal Event Resolution Tasks

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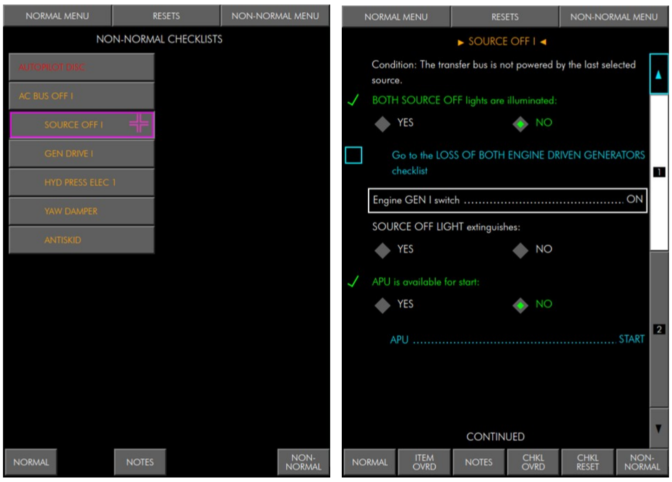
***Abstract*—Non-normal event resolution on aircraft can be challenging on the flight crew with increased time pressure, workload, stress, and other competing tasks that impose a risk on flight safety and burdens the decision-making process. Pilots rely on checklists to aid in their effort, which in its state-of-the-art form are presented on the dedicated Electronic Checklist (ECL) display for Boeing aircraft and on the Electronic Centralised Aircraft Monitor (ECAM) system for Airbus aircraft. However, human-induced errors and limitations remain prevalent. Exploring a different approach from other research efforts, this paper proposes a novel design which assumes automated checklist handling as a viable option to better match the difficulties involved with non-normal events. In a human-in-the-loop experiment with 12 commercial pilots, the design was compared against a reproduced Boeing 787 ECL over two scenarios, an electrical and hydraulic failure. A synthetic setup was used, assuming a touch-based Boeing 737-8 flight deck combined with the Boeing 787 state-of-the-art annunciation systems and displays. Results indicate significant checklist completion time reductions with the proposed design of 31.3% and 42.0% for the electrical and hydraulic failure, respectively. Experienced workload and situation awareness remained unchanged, though compressed in a shorter time frame. The novel display was positively anticipated by participants but was found to lack automation feedback. This paper concludes with the proposal to continue the research on the novel automated ECL since time requirements were significantly lowered and the automation did not negatively impact situation awareness.**

***Index Terms*—Electronic checklists, non-normal events, automation, workload, situation awareness, time to completion.**

I. Introduction

The primary purpose of checklists is to ensure the aircraft is correctly configured for all stages of flight, including non-normal events [1]. They have become conventional on aircraft ever since a fatal crash of a Boeing B-17 in 1935 from which it became clear that aircraft functions and operations have become too complex for pilots to memorise to the full [2] [3]. Two types of checklists are distinguished, Normal Checklists (NC)s and Non-Normal Checklists (NNC)s [4]. NNCs aim to correct, compensate, or otherwise accommodate for an experienced non-normal condition [4] [5]. They are accessible through a Quick Reference Handbook (QRH), a hardcopy manual containing NCs and NNCs. However, QRH-use was prone to numerous issues [4] [6], leading to the development of Electronic Checklists (ECL)s for the Boeing 777 which became certified in 1996 [4] [7].
The ECL collaborates with the Engine Indication and Crew Alerting System (EICAS), which through messages indicates non-normal situations to the flight crew. Upon detection by EICAS, the associated NNC is immediately displayed on the ECL inside the non-normal menu (see Figure 1a), from which the individual NNC can be opened (see Figure 1b). Boeing families equipped with EICAS and ECL displays are the Boeing 777, Boeing 747-8, and the Boeing 787 (see Figure 1). The latest ECL development is the introduction of touchscreens for all forward flight displays on the Boeing 777X, in a push to stimulate work efficiency and intuitiveness. The Airbus electronic checklist derivative is part of the Electronic Centralised Aircraft Monitor (ECAM) system, where instead of allocating two separate displays (EICAS and ECL), an integrated approach on a single display was adopted with the difference that the pilot cannot choose on what checklists to execute. Hereinafter, the Boeing paradigm receives the main focus.



(a) (b)

Fig. 1: Non-normal menu in **(a)** and an opened checklist in **(b)** as displayed on the reproduced Boeing 787 ECL

Notwithstanding the fruitful checklist evolution, human-induced checklist incidents, as reported by the Aviation Safety Reporting System (ASRS), still accumulated for 38% of selected cases for a period between March 2017 and March 2019 [8][1], highlighting room for improvement. Especially in light of the current trend towards Single Pilot Operations

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The proposed design is compared against a reproduced Boeing 787 ECL in a human-in-the-loop experiment wherein 12 commercial pilots conducted two non-normal scenarios, an electrical and a hydraulic failure. The experimental setup assumed the Boeing 737-8 systems and flight deck combined with the Boeing 787 annunciation system and displays which were all operable by touch. In a between-subjects design,

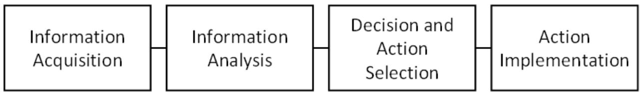


Fig. 2: Four automation classes [34]

each participant was assigned one of the ECL displays (ECL or AECL) to conduct both scenarios and were evaluated in terms of time requirements, experienced workload, situation awareness, decision-making, managing a secondary task, and their design acceptance. Finally, potential automation drawbacks such as complacency [25]–[28], automation bias [29] [30], and skill degradation [31] [32] were not considered for this research.

II. The Proposed Automated ECL

A. Existing Automated Elements of the ECL

Implementing an automated solution for handling checklists requires answers to the questions of what to automate, how much, and when [33]. What is automated can be categorised under four classes, which are based on a simplified four-stage model of human information processing and are adjusted to system functions (see Figure 2) [34].

ECLs already adopt automation within the first three classes. Acquiring information is automated where possible as the aircraft can detect malfunctions. Subsequently, information analysis is covered as well, since the aircraft can integrate information input into a single or multiple EICAS messages with the associated checklists displayed on the ECL. Automatic generation of NNCs comprises decision and action selection as checklists are a script to get the aircraft in the correct configuration and provide supplementary information as well as flight continuation advice (e.g., divert to the nearest suitable airport, avoid icing condition, or limit flight altitude to a certain height). Note that, although it is generally advised against, pilots do have authority to override checklist steps and organise the checklist order at their priority. The action implementation – the execution of the checklist steps – is however still completely manual, although it should be noted that through autosensing the aircraft supervises the pilot's actions for closed loop line items. The proposed design focuses on automating the action implementation class.

B. Automating the Checklist Execution

For describing the Level of Automation (LOA), various taxonomies exist [35]–[37]. The different automation levels consider the division of roles between human and machines, specifically in terms of autonomy – independence of a system to initiate and carry out automation – and authority, which denotes to the automation capability assigned to the system [31]. Establishing an appropriate LOA is vital since different levels are found to affect performance, workload (in NNC context [21]), and situation awareness [38]. Therefore, taking into consideration the effects of different levels of automation and the dynamics of non-normal events, different types of checklist steps are evaluated on automatability, situation awareness, time requirements, and authority for both upside and downside potential when deciding on what to automate.

Firstly, the automatability of checklist steps is assessed. Open loop line items, by its very definition, cannot be automatically sensed by the aircraft and are therefore out of consideration. They require manual completion and confirmation by the pilot and can be recognised on the ECL by the grey box in front of a step (see Figure 3). Furthermore, conditions, objectives, and operational notes do not hold a status of completion. Instead, they exclusively provide information. As such, since there is nothing to complete, there is no possibility of automation. Deferred line items refer to a Normal Checklist (NC) affected by a completed NNC. For example, a deferred line item may describe a change in the action required to complete an NC step, add or replace an individual line item, or introduce a new NC altogether. However, the deferred line items are only to be completed whenever the NC becomes relevant, for example, the Approach NC. Consequently, they are not considered for automation.

Closed loop line items are autosensed by the aircraft and, when assuming the aircraft would be capable of moving switches and selectors, have the potential to be automated. Although automatable, the different types of closed loop line items were assessed if they should be automated.
The need for building situation awareness is already integrated within some of the checklist steps itself, as they can inherently differ in authority. Instructions for certain steps may indicate 'Confirm', which requires a verbal agreement of both pilots before action is taken [39]. Such steps, due to their respective impact, are classified as higher authority. They include an engine thrust lever, an engine start lever, an engine, APU, or cargo fire switch, a generator drive disconnect switch, an IRS mode selector when only one IRS has failed, and a flight control switch [39]. Within the class of confirmation-requiring steps, guarded switches are on the highest level of authority since a guard protects switches before they can be moved into certain positions, in addition to the required verbal pilot agreement. Such is the case for, in example, irreversible steps, which, when effectuated, are permanent and can only be reinstalled through servicing by maintenance. Consequently, any step of higher authority is excluded from automated execution.

After evaluation of the other closed loop line item types, no more were excluded for situation awareness or other concerns. These include conditional line items, off then on, and duplicate closed loop line item steps. Conditional line items take an *if else* approach wherein a set of now superfluous steps are overridden and can be both closed loop and open loop. When closed loop, the Automated ECL (AECL) automatically executes such a step. Off then on is a troubleshooting step by setting a switch off then on within

TABLE I: Overview of what is automated and integrated in the dropdown menu by NNC step type

Step Type	Automated?	Dropdown Menu?
Condition & Objective	No	Yes
Regular Switch	Yes	No
Regular Selector	Yes	No
Open Loop Line Item	No	Yes
Confirm Line Item	No	Yes
Guarded Switch	No	Yes
Irreversible Switch	No	Yes
Timer	Yes	No
Calculation	Yes	Yes
Closed Loop Conditional Line Item[2]	Yes	No
Off then On	Yes	No
Duplicate Closed Loop Line Item	Yes	No
Operational Note	No	Yes
Deferred Line Item	No	No

the same step. Similarly, a duplicate closed loop line item requires the same switch to be in different positions within the same checklist. The issue is that, due to autosensing, only one of the steps can hold the status complete. Thereby checklist completion is compromised since it is now in a loop (it will go back to the first incomplete step of the checklist). The ECL resolves this issue by automatically overriding the previous ‘duplicate’ step(s) once all previous steps are completed. The AECL will follow this logic as well and includes duplicate closed loop line items in the automation attempt.

Some steps are rather time-consuming, such as calculation and timer steps. Non-normal events can cause system performance not to be up to par or the system to become inoperative, which in the case for landing-relevant systems (e.g., brakes and flaps) may increase the required landing distance. Pilots can address dedicated landing tables in the QRH to realign expectations of the aircraft landing distance accordingly. Such calculations are automatically performed with the AECL, which displays the output and output-yielding inputs (see Figure 3 for an example). Timer steps ask the pilot to wait for a certain amount of time (generally a few minutes) and are already automatically performed by the Boeing 787 ECL by displaying the time left. The AECL will also show the remaining time as well as integrating timer steps into the automation. An overview of all step types and whether they are automated is presented in Table I.

Accredited initial automation autonomy to the AECL is low, due to the specificity and uniqueness of non-normal events, which cannot in all circumstances be adequately anticipated by designers. As such, at the pilot’s discretion, automation is initiated. Beyond the initiation stage, autonomy is higher since automation will continue until finished, unless otherwise

[2]Conditional line items can be both open loop and closed loop

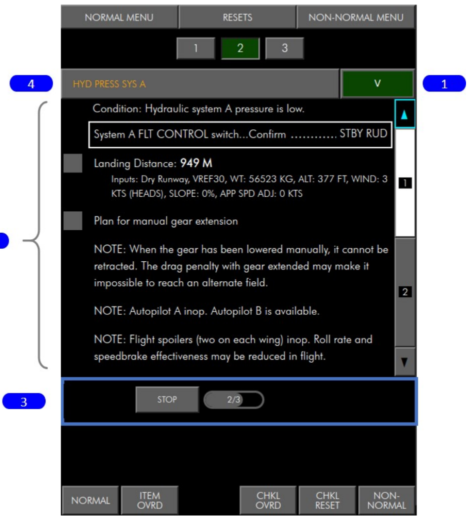


Fig. 3: By pressing the arrow on the right-hand side **(1)**, the dropdown menu can be opened and closed. The dropdown menu itself consists of the reduced checklist content **(2)** and a row from which automation and checklist progress is controlled and supervised **(3)**. When deemed necessary, the complete checklist can be accessed by pressing the checklist name **(4)**, alike on the Boeing 787 ECL

instructed by the human operator. This describes an adaptive system wherein the human allocates the role of checklists execution. The potential drawback, however, is an increased mental workload due to the added function allocation task [25].

C. The Dropdown Menu

Inspired by Airbus’ ECAM and the comparable ECL integrated into EICAS study by Li et al. [23], this research reassessed the location of checklist information presentation. Opting for a more integrated approach, checklists with the AECL can be processed from inside the checklist menu, instead of in isolation as is the case on the ECL.

Within the non-normal menu, checklists can be expanded and collapsed by pressing the right-side arrow button (see Figure 3). The expandable checklist is referred to as the dropdown menu, consisting of two main domains: the checklist content and a row from which automation and checklist progress is handled (see Figure 3). Presented content includes conditions, objectives, operational notes, open loop line items, closed loop line items of higher authority, and landing distance calculation output. Steps are included as they either present useful information or require pilot input in order to be completed. It excludes any automated steps and other non-relevant information to the pilot. The latter refers to steps overridden by conditional line items, which through an *if else* approach affects the continuation of a checklist by overriding the set of steps no longer relevant. As a result, some checklists on the ECL may appear relatively cluttered when compared against the AECL. Figure 4 depicts an example as a comparison between the reproduced Boeing 787 ECL and the AECL for the Source Off NNC.

(a) ECL (1/2) (b) ECL (2/2) (c) AECL

Fig. 4: The Source Off NNC displayed on the ECL is shown in **(a)** and **(b)** for page 1 and page 2, respectively. The non-relevant overridden steps are in blue and make the display relatively cluttered when compared against the AECL in **(c)**

To avoid displaying non-relevant information, the AECL dropdown menu dynamically updates when necessary after completing a conditional line item (an example is shown in Figure 5). The aim of the AECL is thus to present pertinent content only in a neat and efficient fashion. Nevertheless, the checklist as a whole is still accessible, like on the ECL, to provide flexibility since, depending on scenario circumstances and pilot knowledge and situation awareness, reviewing the grander checklist may be desired to gain further context (see Figure 3). For example, when the pilot would like to review the NNC's deferred line items, as they are not shared in the dropdown menu. An overview of what step types are included in the AECL's dropdown menu is presented in Table I.

Whenever a checklist contains automatable steps, the automation button can be pressed on the left to commence the automation (see Figure 5a). With automation in progress, the operator has the possibility to stop automation and is presented with an automation progress bar, which reports the fraction of the number of steps completed through automation divided by the total number of automatable steps (see Figure 5b). Once completed, the progress bar displays 'Done', as shown in Figure 5c. Additionally, from Figure 5c, it can also be observed that the checklist content was updated with two open loop line items due to a conditional line item (see Figure 5d for reference). After completing the remaining steps, the checklist displays its status of completion through the green bar stating 'Checklist Complete' (see Figure 5e). Additionally, as shown in Figure 5f, the clear button on the right appears by which the operator can eliminate the checklist from the non-normal menu.

D. *Preliminary Results of the AECL*

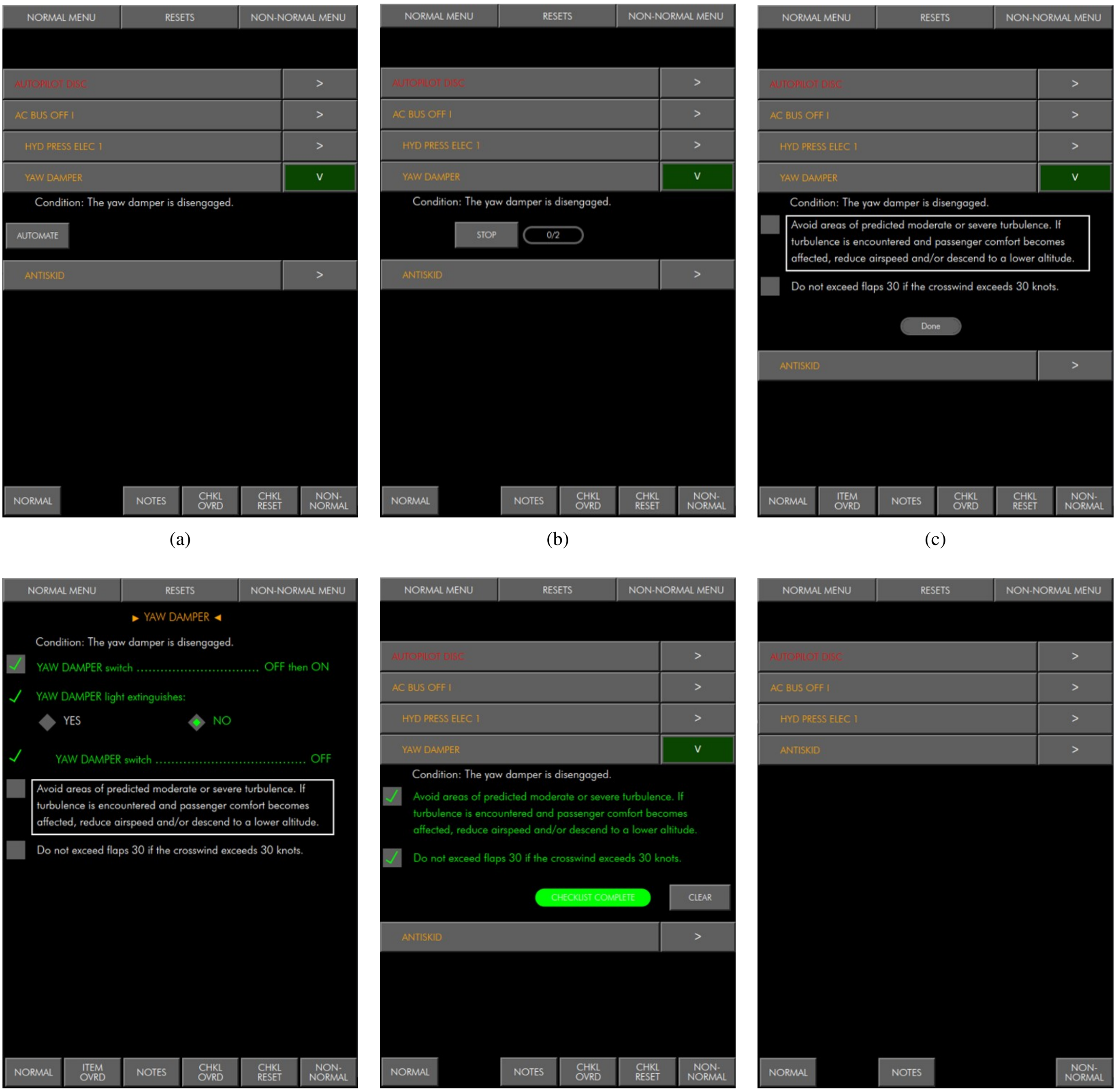
For the checklists shown in Figure 3 and Figure 5 (the Loss of System A checklist and the Yaw Damper checklist), the number of steps to be performed by the pilot is reduced by 66.67% and 60.0%, respectively. Overall, the number of steps for the drive shaft failure scenario is reduced by 53.6%, whereas for the hydraulic leak failure scenario, the figure reduced with 62.5%.

III. Experiment Design

The objective of this experiment was to compare the most state-of-the-art ECL, the reproduced Boeing 787 ECL (baseline), against this research' proposed design, the AECL. In a human-in-the-loop experiment, key evaluation criteria such as experienced workload, situation awareness, and time to completion were compared in two separate scenarios on a reproduced Boeing 737 touchscreen flight deck, which adopted the Boeing 787 checklist annunciation systems.

A. *Participants*

In total, 14 participants volunteered to partake in the experiment. Due to the specific system knowledge requirements of the experiment, the participants are or were all recently active professional airline pilots on the Boeing 737, of which a brief profile is presented in Table II. Due to a steep learning curve involved for learning a new display and annunciation process and to avoid scenario recognisability, the experiment used a between-subject design. Thereby, every participant was assigned a single display with which two scenarios were conducted. The order in which the two



(a) (b) (c)

(d) (e) (f)

Fig. 5: Checklist automation is started in **(a)**, in progress in **(b)**, and finished in **(c)**. Additionally, through conditional line items, the checklist content is dynamically updated in **(c)** with two more open loop line items. In **(d)**, the AECL is compared against the reproduced Boeing 787 ECL at the current state of progress, from which it can be observed that three out of fives steps are automated and not in the dropdown menu. After completing the remaining two open loop line items in **(e)**, the AECL displays a green bar stating ‘Checklist Complete’. Finally, in **(f)**, the checklist is now ‘cleared’ from the non-normal menu

TABLE II: Participant background information[3]

	Age	Total commercial flight hours	Boeing 737 flight hours	Profile
ECL				
Max	61	21,000	9,000	4 Captains and
Min	28	2,900	100	2 First Officers
Average	44	10,150	4,392	
AECL				
Max	50	12,000	11,500	2 Captains and
Min	27	3,500	2,000	4 First Officers
Average	35	6,800	4,600	

scenarios were presented was equally distributed within both groups. Furthermore, two participants were type-rated on the Boeing 787 and therefore already had experience with EICAS and the ECL. They were equally divided over the two groups as well.

B. Task and Instructions

The experimental scenario consisted of a flight departing from Almaty (UAAA), Kazakhstan to planned destination Roshchino (USTR), Russia and included one option as destination alternate, Kostanay (UAUU), Kazakhstan (see Figure 6). The locations were selected to avoid participants having previous experience with the aforementioned airports. Although GPS locations and certain airport-specific information were adopted, information about the weather, runways, and approach NAVAIDs was altered to fit experiment needs and to avoid prior participant knowledge bias. Notable differences between destination and destination alternate are the distance (UAUU was closer from where the failures occurred) and the available runways and approaches. Both airports retained LOC-ILS approaches, three at USTR and one at UAUU, whereas UAUU also offered an Area Navigation (RNAV) approach. However, NOTAMs communicated that the single LOC-ILS approach runway at UAUU was inoperative at the time of flight and that no visual or circling approaches were allowed, forcing the aircraft to conduct the still available RNAV approach when diverting. To summarise, the following approaches were available per airport:

- Planned destination (USTR): 3x LOC-ILS.
- Destination alternate (UAUU): 1x RNAV.

Additionally, participants were provided with key aircraft information such as weights, a callsign, and that they were dispatched with an inoperative Auxiliary Power Unit (APU) (see Table III for an overview of key general aircraft and weight information as presented to the participant).

For each design, a participant completed two scenarios in which a failure occurred during the flight, an electrical

[3]Only includes the participants used for the data analysis

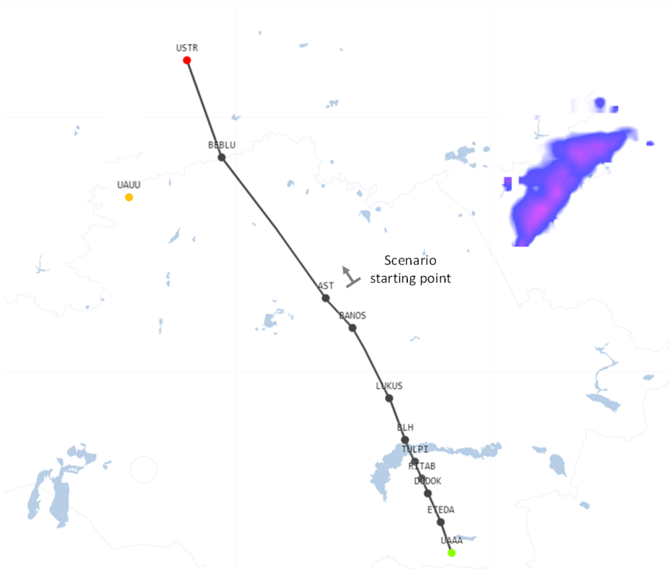


Fig. 6: Map of the experiment flight plan

TABLE III: Key general aircraft and weight information

Weights (Kg)		Other	
Load in compartments	1,704	Callsign	DUT 961
Passenger/cabin bag	9,124	Cruise altitude	FL350
Total traffic load	10,828	PAX	87
Dry operating weight	41,077	APU	Inoperative
Zero fuel weight	51,905		
Take off fuel	11,133		
Take off weight actual	63,038		
Trip fuel	7,105		
Landing weight actual	55,932		

and a hydraulic failure. Both scenarios assumed the same flight plan and the failure occurred approximately at the same instance, a few minutes after passing waypoint AST, from which the simulation commenced. The participants were tasked to resolve the abnormal situation when such an event would arise. Accordingly, this would require to get the aircraft in the correct configuration, and as such, all incurred checklists were to be completed. Meanwhile, the participant needed to construct a plan of approach on how to continue the flight within the context of the flight plan, wherein factors such as operational feasibility and safety were to be considered. For example, one may opt to divert to UAUU, to continue as planned to USTR, or go back to the departure airport. Together, this tests checklist handling and the decision-making process.

Also, the participants performed a secondary task. Over set intervals, five prerecorded Air Traffic Control (ATC) messages were communicated to the participant, asking to report back a particular aircraft state or element of the flight plan (e.g., flight speed, altitude, next waypoint). One of the

messages corresponded to the correct callsign (DUT[4] 961, pronounced Delta Uniform Tango Niner Six One) and the order and content of the messages were randomised to avoid learning. The secondary task increases workload demand and tests the ability to coordinate more than just one task and to what the degree a participant is tunnelled into the display.
Finally, participants assumed the Pilot Non-Flying (PNF) role and could ignore any substantial tasks generally assigned to the Pilot Flying, and were thus not concerned with flying the aircraft.

C. Independent Variables

The experiment was conducted over two dimensions of independent variables:

- Electronic Checklist designs, and
- Scenarios.

The two ECL designs are a between-subject independent variable which compares the reproduced Boeing 787 ECL against the AECL. For both displays, participants completed two scenarios – a drive shaft failure and a hydraulic failure – under the same conditions. In contrast to the drive shaft failure, the hydraulic failure is a more commonly trained scenario for pilot training. Evaluating two of such scenarios is important since often-trained scenarios are found to be handled much better [19] [20]. The scenarios have been verified through a level D simulator of MPS[5] by failing the Boeing 737-8 systems as described hereinafter.

Drive Shaft Failure

The electrical system on the Boeing 737 has two principles: there is no paralleling of the AC sources of power, and the source of power being connected to a transfer bus automatically disconnects the existing source [40].
The electrical system has three main divisions: the Alternating Current (AC) power system, the Direct Current (DC) power system, and the standby power system. Two engine Integrated Drive Generators (IDG)s provide primary electrical power and supply three-phase 115 volt, 400 cycle AC. Each of the IDGs supplies power to its respective AC transfer bus through a generator circuit breaker during normal operations. In case of a failing IDG, the Bus Tie Breaker (BTB) system will allow both AC transfer busses to be supplied by the remaining IDG, which can be achieved by closing both BTB 1 and BTB 2. Additionally, when available, the APU operates a generator and can supply power to both AC transfer busses. The Transformer Rectifier (TR) units and the main battery supply DC power.
TR 1 and TR 2 are supplied with AC power from AC transfer bus 1 and AC transfer bus 2, respectively. Additionally, a third TR is responsible as backup and as a primary power source for the battery bus. The DC system consists of three busses: DC bus 1, DC bus 2, and the battery bus. The main and auxiliary batteries also supply backup power to both the standby AC and standby DC systems. A schematic overview of the electrical system is presented in Figure 7.

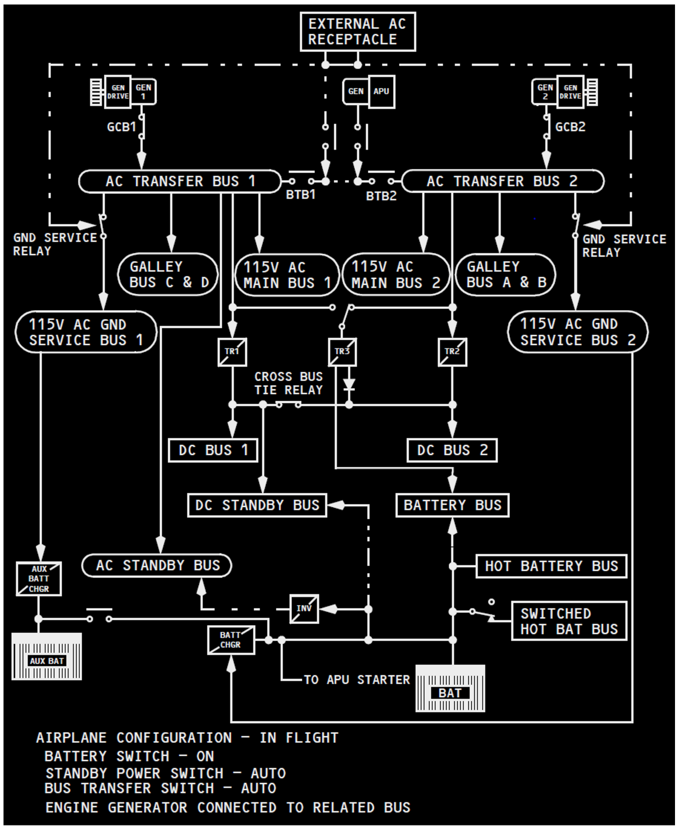


Fig. 7: Electrical system schematic of the Boeing 737-8 [40]

The scenario was modelled as a failing drive shaft on the left-hand side. This caused the DRIVE 1 light on the overhead panel to illuminate and EICAS to display the corresponding message. Since no APU was available to compensate, and to keep both AC transfer busses supplied, the system will close the BTBs to connect the right IDG to both transfer busses. However, the BTBs for this scenario were not functioning as expected and AC transfer bus 1 did not receive the required electrical power, causing AC transfer bus 1 to stop working. This resulted in the illumination of the SOURCE OFF and TRANSFER BUS OFF lights on the left side and two more messages on EICAS. Also, the A-side autopilot (which was engaged) was now disconnected and the autopilot disconnect horn sounded. Autopilot B, however, was still available and could be connected. By now, both the warning and caution lights illuminated on the master caution system. AC transfer bus 1 is solely responsible for powering various subsystems, which shortly failed after the loss of AC transfer bus 1. Subsequent annunciations on the overhead panel and EICAS were the YAW DAMPER, LOW PRESSURE lights for fuel pump 1 FWD, fuel pump 2 AFT, and hydraulic pump ELEC 1, TEMP PROBE, L ALPHA VANE, and L ELEV PITOT

[4]Delft University of Technology
[5]Multi Pilot Simulations BV

heat lights, and window OVERHEAT lights for L FWD and R SIDE. Each of which providing the associated checklist on the ECL. Additionally, ANTISKID, with an associated checklist on the ECL, is reported on EICAS as well as GPWS INOP and HIGH ALT LAND INOP which also were annunciated through the INOP light on the aft pedestal. All annunciations and checklists appeared within approximately 4 seconds after the first illumination (which was the DRIVE 1 light). In Figure 10a and Figure 10b, the EICAS messages as presented during the experiment are shown, whereas Figure 9 indicates the experienced illuminations on the overhead panel for the drive shaft failure.

Hydraulic Leak Failure

The Boeing 737 has three hydraulic systems: system A, system B, and the standby system. Both system A and system B are pressurised by bleed air and operate independently. They can separately power all flight controls with no decrease in aeroplane controllability [40]. All three systems have a reservoir, pumps, and filters, which pressure the reservoirs at 3,000 psi under normal conditions. Together, the hydraulic systems power: flight controls, leading-edge flaps and slats, trailing-edge flaps, landing gear, wheel brakes, nose wheel steering, thrust reverses, and autopilots.
More specifically, hydraulic system A is responsible for powering the following: ailerons, rudder, elevator, flight spoilers (two on each wing), ground spoilers, alternate brakes, engine 1 thrust reverser, autopilot A, normal nose wheel steering, landing gear, and the power transfer unit. Hydraulic system B, on the other hand, is responsible for powering the following components: ailerons, rudder, elevator, flight spoilers (two on each wing), leading-edge flaps and slats, normal brakes, engine 2 thrust reverser, autopilot B, alternate gear retraction, alternate nose wheel steering, and the yaw damper. The standby system powers the thrust reversers, rudder, leading-edge flaps and slats (full extend only), and the standby yaw damper. A schematic overview of the Boeing 737-8 hydraulic system is shown in Figure 8.

The hydraulic leak was assumed to be relatively large, causing a loss of 10 gallons per minute in reservoir A. Once the reservoir quantity dropped below 18.7% of a full tank, the LOW PRESSURE lights of ENG 1 and ELEC 2 of system A on the overhead panel illuminated. After approximately 30 seconds, the system A flight controls were annunciated on the overhead, and the corresponding message was displayed on EICAS. Also, the FEEL DIFF PRESS light illuminated as a result of the hydraulic system A pressure dropping more than 25% relative to hydraulic system B. Autopilot A, the engaged autopilot, was disconnected and the horn sounded, however, Autopilot B was available and could be engaged. The master caution system illuminated both warning and caution. In case the hydraulic system was not shut down within approximately one minute, the electric hydraulic pump OVERHEAT light illuminated with the associated message shown on EICAS. An overview of the EICAS messages and

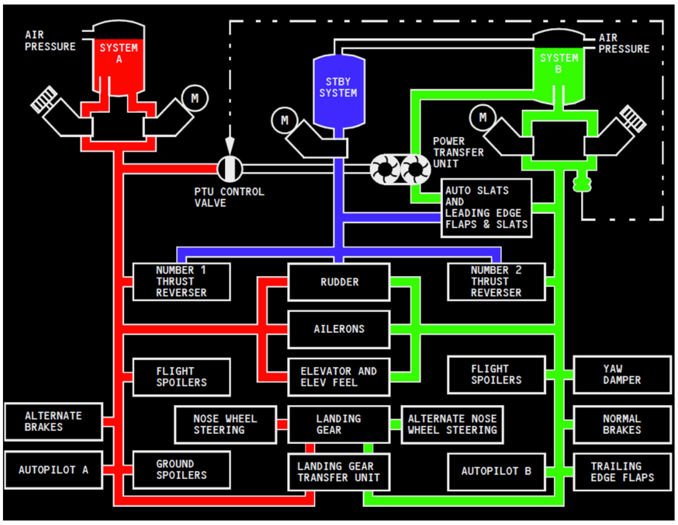


Fig. 8: Hydraulic system schematic of the Boeing 737-8 [40]

the overhead panel illuminations are shown in Figure 10c and Figure 9, respectively.

D. *Control Variables*

The control variables of the experiment were:

- Concurrent task: a parallel task which required participants to respond to ATC messages throughout each scenario to increase participant workload and add realism. Also, concurrent tasks are often a constraining factor during non-normal events [19] and situation awareness development [41].
- Checklists: the checklist content was presented as per the Boeing 737-8 QRH [39].
- Pilots: aircraft type rating, experience in flight hours, flight deck position, and current employer.
- Apparatus: following Figure 11, **(1)** was presented on a 15” 4:3 XGA touchscreen, **(2)** on a 42” 9:16 UHD touchscreen, **(4)** and **(5)** on a 21.5” 16:9 FHD touchscreen, **(6)** on a 15.6” 16:9 FHD touchscreen, and **(7)** on a 19.5” 9:16 FHD touchscreen. Additionally, the overhead panel was positioned in a 25 degree inclination, similar as on the Boeing 737-8.
- Training: the amount and thoroughness of training the participants received before starting the experiment.
- Flight plan: what information was presented before starting the scenarios and how this was communicated to the pilot.
- Automation speed: the assumed time required by automation to move a switch to a certain position. For the experiment, this value was set at 0.5 seconds to guarantee a switch is in its correct position and give the flight deck ample time to recognise the new configuration before advancing.

Fig. 9: The overhead panel of the Boeing 737-8. Indicated in blue are the lights illuminated during the drive shaft failure, whereas indications in orange represent the illuminations experienced during the hydraulic leak failure

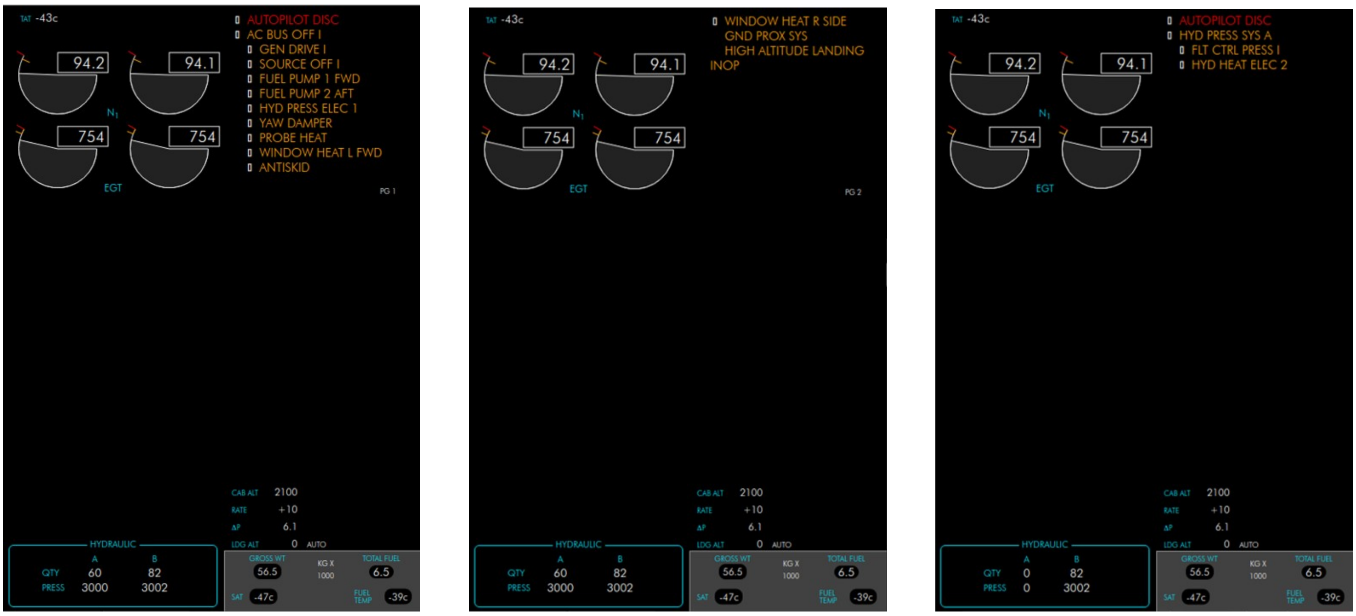
E. Dependent Measures

The dependent measures of the experiment were:

- Experienced workload,
- Situation awareness,
- Performance,
- Choice of airport,
- Concurrent task, and
- Acceptance.

Experienced workload was subjectively measured post-scenario using the Rating Scale Mental Effort (RSME) [42], a language-calibrated scale from 0 to 150 complemented with text indications to guide the participant's own ratings. Situation awareness was measured with the Situation Awareness Rating Technique (SART) [43], a post-trial subjective technique which utilises ten dimensions to obtain a single consolidated score. Both RSME and SART were only tested after each scenario to overcome unwanted intrusions and workload during the testing.

Performance is appraised as a time variable, or time to completion. Two variants of completion times were assessed, the time to set the aircraft in the correct configuration following the NNCs (gross) and the time to completion when only counting time spent actually completing the checklists itself (net). Accuracy was deliberately disregarded since both ECLs only allow a checklist to acquire a status of completion when all steps are completed correctly. Furthermore, at the participant's discretion, a step may sometimes be intentionally ignored by overriding the line item, resulting in an incomparable measure. The choice of airport (destination,



(a) Drive shaft failure (1/2) (b) Drive shaft failure (2/2) (c) Hydraulic leak failure

Fig. 10: Overview of EICAS messages presented to the participant for the drive shaft failure in **(a)** (messages page 1) and **(b)** (messages page 2) and the hydraulic leak failure in **(c)**

destination alternate, or departure) was registered, as well as the time by which such decision was made. The concurrent task score was obtained by determining the accuracy with which a participant responded to the correct callsign with the correct answer.

Finally, after the experiment, the acceptance of both displays was assessed to identify if the design was deemed effective and suitable. Following a Crew Acceptance Rating Scale (CARS) [44] flow diagram, the participant indicated a score from 1 to 10.

F. Apparatus

The experiment was conducted in a flat panel trainer setup assuming the Boeing 737-8 cockpit and systems from the point of view of the left-positioned pilot, for this experiment the PNF. However, the 737 family does not have either the EICAS or ECL display. The two displays were taken from the Boeing 787, which is considered as state-of-the-art. This research thus adopted a synthetic flight deck, taking parts of the most advanced pieces of Boeing aircraft (EICAS, ECL, and touchscreen technology) and integrate this onto the Boeing 737-8 simulation platform.

Following Figure 11, the ECL **(1)** was positioned between the aft pedestal **(7)** and the row of displays in front of the participant. The row contained, from left to right, the master caution **(6)**, the Primary Flight Display (PFD) **(5)**, Navigation Display (ND), and EICAS (together **(4)**). The overhead panel **(2)** was positioned above the pilot at the same inclination as in the Boeing 737-8 cockpit. Finally, the Mode Control Panel (MCP) **(3)** was placed on top of the two screens in front of the participant. All screens, and the thereon presented panels and displays, were operable by touch. The exception, however, was the MCP, which was still mechanical.

Fig. 11: Experiment apparatus

G. Training

A dedicated training scenario with made-up checklists was performed multiple times to make sure the participant was fluent in navigating the display and the touch flight deck before beginning the measurement stage. To emphasise on this, a hypothetical non-normal scenario was constructed. Herein, no logical system knowledge was required; rather, the focus was on the participant becoming affluent with any type of action required during the experiment. This would include, the various step types from Table I, a disconnecting autopilot, and the various functions of the ECL/AECL display. During the briefing, specific instructions were communicated that, for the AECL, checklist completion was only to be performed through automation, in order to guarantee the design was used as intended. Nonetheless, it was allowed to access the checklist before and after the completion process to give the opportunity to develop context where needed.

H. Procedure

The experiment was approved by the TU Delft Human Resource Ethics Committee and, before starting the experiment, participants were required to sign an informed consent form.

The experiment started with a technical briefing, discussing the flight deck, EICAS, the relevant ECL display (ECL or AECL), the flight plan, and the tasks at hand (primary and secondary). Subsequently, the training phase set off which was repeated until both the participant and experimenter were completely comfortable with the participant's fluency in operating the display and flight deck in order to avoid mistakes attributable to display and flight deck unfamiliarity.
After the briefing and training, two measurement scenarios were completed: the drive shaft failure and the hydraulic leak failure, each succeeded by participants indicating their experienced workload, situation awareness, and commentary on their decision rationale and thoughts on the nature of the failure. The order of the scenarios presented was equally distributed within both groups by following a Latin Square design.
A short debrief was administered when both scenarios were completed, which asked participants to indicate an acceptance score and to provide feedback on the design and touch flight deck. In total, the experiment duration averaged around 3-3.5 hours per participant.

I. Hypotheses

It was hypothesised that for the AECL, when compared against the baseline ECL:

- Experienced workload decreases as a result of automation.
- Time to completion decreases. With automation, less time is required to get the aircraft in the correct configuration. Moreover, since less attention shifting is required when omitting the manual work, participants can better focus on solving the non-normal event.
- Situation awareness is expected to remain unchanged. The automated design might suffer from out-of-the-loop complications [45] in terms of perception, since part of the aircraft's non-normal configuration is no longer done manually. However, such effects are expected to be minimal and not influence results. On the other hand, situation awareness may increase because of the freed cognitive resources due to the automation, which would allow for better comprehension and projection of future status. Again such effects are expected marginal since every participant during the experiment is not constrained in time.
- The concurrent task score is expected higher due to a product of lower expected experienced workload (and thus an enhanced capability to manage other tasks) and less attentional tunnelling when not manually completing steps.

IV. Results

Seven participants per display completed the experiment, but data from two participants (one from each group) were removed as one did not complete the scenarios as instructed and the other because of incomplete data. Furthermore, parametric assumptions were violated for the between-subjects setup, and due to the small sample size, six for both displays, the Mann-Whitney U test is utilised where applicable.

A. Time to Completion

Time to completion is assessed in two ways. First, the gross value is analysed, which describes the time required to finish all checklists, and secondly, the net time to completion is considered, which considers the time actually spent with the checklists.

The gross time to completion results are visualised in Figure 12. With the AECL, the median is considerably lower for the drive shaft failure (ECL: Mdn = 832.8, AECL: Mdn = 602.2) and the hydraulic leak failure (ECL: Mdn = 348.5, AECL: Mdn = 240.4), with a drop of 27.7% and 31.0%, respectively. Statistical results, however, do not report significance for the drive shaft failure scenario (U = 9.0, p = 0.087) and the hydraulic leak failure scenario (U = 10.0, p = 0.115). This may be partially affected by one participant achieving extreme scores with the ECL display. Apart from this participant, all of the participants using the AECL achieved lower times to completion for the drive shaft failure, except the AECL diamond, which time to completion equalled the lower end of the ECL display. Similar trends can be observed for the hydraulic leak failure, where the AECL's time to completions are in the low range of the ECL display. Additionally, time to completion across all participants is very consistent for the AECL display in the hydraulic leak failure scenario. This is

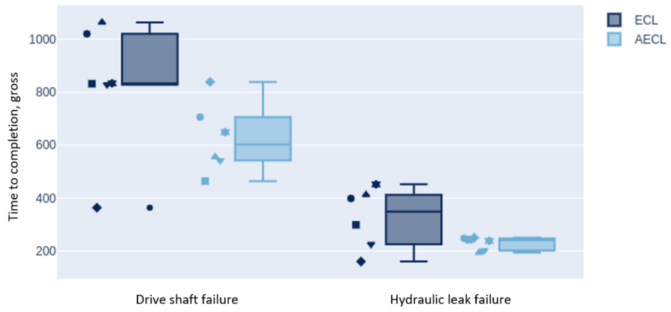


Fig. 12: Time to completion, gross

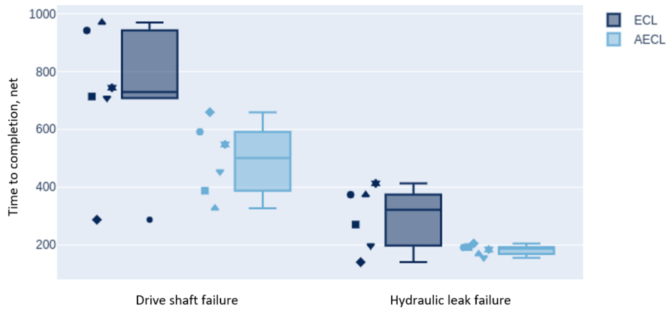


Fig. 13: Time to completion, net

likely the consequence of the hydraulic leak failure scenario only having one substantial checklist (loss of system A), wherewith the drive shaft failure scenario 12 checklists appear.

The net time of completion, on the other hand, does show a significance for both the drive shaft failure (U = 6.0, p = 0.033) and the hydraulic leak failure (U = 7.0, p = 0.046). Most likely, this measure better articulates the increased time efficiency of the AECL since the datapoints of the AECL display decrease more relative to the ECL display, as can be observed when comparing Figure 13 with Figure 12. The net time to completion medians are reduced by 31.3% for the drive shaft failure scenario (ECL: Mdn = 728.8, AECL: Mdn = 500.7) and 42.0% for the hydraulic leak scenario (ECL: Mdn = 322.1, AECL: Mdn = 187.0).

B. Experienced Workload

The subjectively indicated RSME workload per design for both scenarios is shown in Figure 14, with a higher median for the AECL display in the drive shaft failure scenario (ECL: Mdn = 37.5, AECL: Mdn = 50.0) and a slightly lower median in the hydraulic leak failure scenario (ECL: Mdn = 32.5, AECL: Mdn = 32.0). The Mann-Whitney U test reveals no significant effect in the drive shaft failure scenario (U = 15.0, p = 0.343) and the hydraulic leak failure (U = 16.0, p = 0.404). Examining Figure 14 more closely reveals that for the AECL, especially one participant indicated higher experienced workloads. Also, the experienced workload scores are relatively widely spread for all experiment conditions,

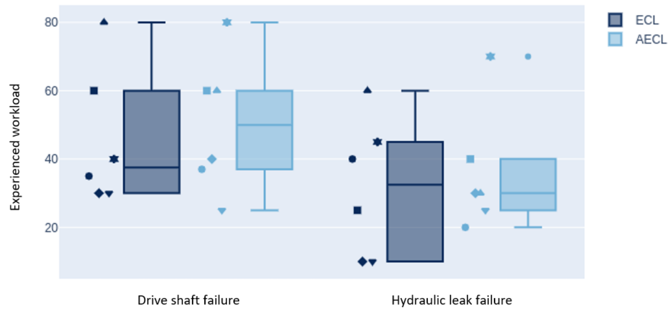


Fig. 14: Experienced workload ratings

perhaps with the exception for the AECL in the hydraulic leak failure, which is more condensed apart from one outlier. Nonetheless, this would indicate a large variation on an individual basis and a recurrence of participants near the extremes.
The results indicate no difference between both designs in terms of experienced workload, which does not support the hypothesis.

C. Situation Awareness

The situation awareness SART measurements are displayed in Figure 15 (note that the scores are from high to low). When consulting the Mann-Whitney U test, results are insignificant for the drive shaft failure (U = 13.0, p = 0.234) and the hydraulic leak failure (U = 13.0, p = 0.235). Median values are however higher for the ECL display across both the drive shaft failure (ECL: Mdn = 18.5, AECL: Mdn = 15.0) and the hydraulic leak failure (ECL: Mdn = 21.0, AECL: Mdn = 16.5) scenarios, partially driven by the outlier of the ECL display. Another interesting observation is the more defined range of situation awareness for the ECL display, as the AECL values are more diffused in both scenarios.

The statistical insignificance and data observations indicate no difference in situation awareness for both displays and would support the hypothesis that despite the introduction of automation, no significant impairment of situation awareness occurs. This includes automation side effects such as becoming out-of-the-loop. Participant comments, on the other hand, proved otherwise. It was a deliberate design choice to minimise any information shown and that participants would have context enough to understand what switches and selectors were operated by the automation. Although most participants were reasonably confident, the desire for more feedback about the ultimate automation results was unanimous. Such commentary was mentioned in the post-experiment questions, either in asking about participant trust in automation or in what could be improved on the current design.

Finally, in context of the hypothesis, it cannot be concluded to what extent automation negatively contributed due to

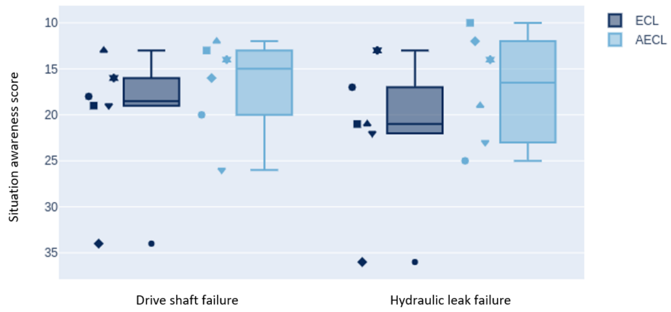


Fig. 15: Situation awareness scores

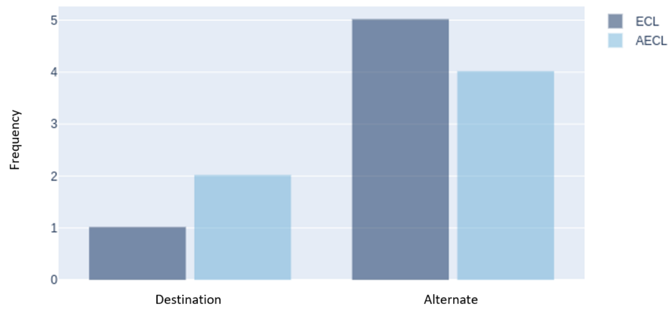


Fig. 16: Choice of airport frequency for the drive shaft failure scenario

being out-of-the-loop and how much it positively influenced participants through freed cognitive resources to be allocated to develop situation awareness.

D. Choice of Airport

Upon experiencing a failure, participants had the choice to either continue as planned, or choose to divert to destination alternate. For the drive shaft scenario, the checklists communicated to the pilot to land at the nearest suitable airport. Destination alternate is the nearest airport, and hence, the task is to determine if it is suitable. As the scenario is set up, the question is whether it is authorised to conduct an RNAV approach with the incurred failures and land safely on the runway. Other literature indicates that with the same failure, RNAV approaches are no longer approved when AC transfer bus 1 and the APU are inoperative [14]. However, as per the operating manuals for some of the airline companies of which participants took part in the experiment, the minimum RNAV requirements were not violated. Likely this is the result of the ongoing development of airline companies' risk position towards RNAV approaches. As such, both options are possible. The added distance of the planned destination is not substantially greater and would be commercially and operationally more attractive. On the other hand, in some cases, the specific checklist instruction of landing at the nearest airport would be ignored when not diverting to destination alternate.
For the hydraulic failure, the best option is to continue as planned, since after losing hydraulic system A, there is still hydraulic redundancy left with hydraulic system B and the standby hydraulic system. Moreover, both hydraulic system A and B are capable of single-handedly powering flight controls without losing controllability [40]. However, the choice of airport is one of full commitment since the landing gear has to be lowered manually, increasing deployment time, and it can, once extended, no longer be retracted. As a result, the aircraft suffers from a permanent drag penalty, making other airports unreachable after a landing attempt. Therefore, when selecting destination alternate, one becomes fully reliable on one runway and takes a more risky option.

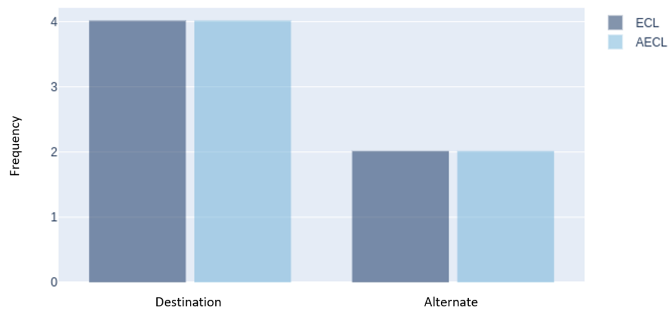


Fig. 17: Choice of airport frequency for the hydraulic leak failure scenario

For the drive shaft failure, four out of six participants diverted with the AECL display, whereas for the ECL five out of six chose to divert, as can be seen in Figure 16. The time required to form a decision is shown in Figure 18, where the AECL achieved lower median values compared to the ECL display (ECL: Mdn = 474.7, AECL: Mdn = 233.2). The Mann-Whitney U test indeed reveals a significantly lower decision time for the AECL (U = 7.0, p = 0.046).
Interestingly, after investigation of experiment video recordings and post-scenario commentary, none of the participants considered whether an RNAV approach was still authorised, including participants for which their current airline does not approve RNAV approaches under this failure. Post experiment, participants were asked to describe to the best of their knowledge, the nature of the failure and what drove their decision for the selected airport.

With the hydraulic leak failure, for both designs, participants diverted two out of six times, as shown in Figure 17. Again, Figure 18 reveals a lower median decision time for the AECL display (ECL: Mdn = 328.6, AECL: Mdn = 157.7), and when consulting the Mann-Whitney U test, the lower decision time is found to be significant (U = 7.0, p = 0.046). Therefore, the AECL display shows significant time reductions for both scenarios in formulating a decision when compared against the ECL display.

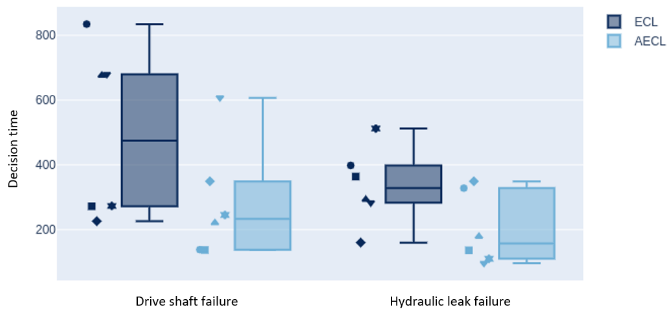


Fig. 18: Decision time

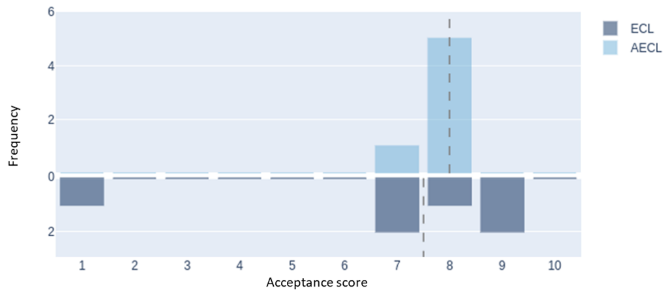


Fig. 19: Acceptance scores

TABLE IV: Correct or incorrect completion of the concurrent tasks per participant after introduction of a failure

		Drive shaft failure					Hydraulic leak failure		
	Participant	1	2	3	4	Accuracy[6]	1	2	Accuracy[7]
ECL	1	×	✓	✓	✓	67%	✓	✓	100%
	2	✓	✓	✓	×	100%	✓		100%
	3	✓	✓	✓		100%	✓	✓	100%
	4	×	✓	✓	✓	67%	✓	✓	100%
	5	✓	✓	✓	✓	100%	✓		100%
	6	×	✓	×	×	33%	×	✓	0%
AECL	7	×	✓	✓		67%	×		0%
	8	✓	✓	✓		100%	×		0%
	9	✓	✓	✓	✓	100%	✓		100%
	10	×	✓	✓		67%	✓		100%
	11	✓	✓	✓		100%	✓	✓	100%
	12	✓	✓	✓		100%	✓		100%
Accuracy, ECL		50%	100%	83%	60%		83%	100%	
Accuracy, AECL		67%	100%	100%	100%		67%	100%	

E. *Concurrent Task*

The concurrent task score indicates the accuracy by which a participant completed the challenge-response task. Per scenario, Table IV shows whether the participant successfully completed each concurrent task, in which only data points after introduction of the failure were considered. Since participants had varying times of completion and the concurrent tasks were initiated at set time intervals, some participants completed more tasks than others. To negate this effect for the statistical analysis, only the concurrent tasks performed by every participant per scenario after introduction of the failure (three for the drive shaft failure and one for the hydraulic leak failure) are included. Table IV shows little difference between both designs for the concurrent task accuracy. For the hydraulic leak failure, it can be observed that one more participant achieved a perfect score with the ECL display, which has no effect on the median values (ECL: Mdn = 100.0%, AECL: Mdn = 100.0%). Unsurprisingly, the Mann-Whitney U test reveals no significance (U = 15.0, p = 0.297). For the drive shaft failure scenario, the AECL slightly outperforms (ECL: Mdn = 83.3%, AECL: Mdn = 100.0%), but no significance was found (U = 14.0, p = 0.261).

[6]Only includes the first three data points

F. *Acceptance*

The acceptance scores obtained through the CARS measurement are summarised in Figure 19 for the ECL and AECL display. When observing the figure, the AECL has a more apparent consensus, with five out of six results equalling 8 out of 10. The ECL shows more variability with scores mainly ranging between 7 and 9 and an outlier of 1. The outlier participant commented that the ECL negatively affected situation awareness and lacked overview. Furthermore, the AECL has a slightly higher median value (ECL: Mdn = 7.5, AECL: Mdn = 8.0). This difference, however, is found not to be significant according to the Mann-Whitney U test (U = 16.5, p = 0.431).
As already mentioned, participants reported a lack of automation feedback, possibly capping the acceptance score at 8 for the AECL display.

V. Discussion

The goal of this research was to investigate the effects of adopting an automation effort to improve the ECL for non-normal situations, an attempt to achieve lower workload and time requirements, while maintaining situation awareness. Results revealed that particularly time requirements in terms of completing a checklist and decision-making were significantly reduced with the AECL.

The time required for a participant to get the flight deck in the correct configuration reduced by 27.7% for the drive shaft failure and with 31.0% for the hydraulic leak failure, which converts to a gain of 3 minutes and 51 seconds and 1 minute and 48 seconds, respectively. Counting only the time spent inside checklists further amplifies the percentage difference to 31.1% for the drive shaft failure and 42.0% for the hydraulic leak failure. The gross time to completion did not differ significantly. However, the net time to completion did, which is arguably the better measure since it directly compares the time allocated to checklists. On the other hand, the gross value does include factors such as the participant rationalising the failure and deciding upon next steps. Nonetheless, time reductions for the AECL are substantial and indicate a more adequate approach to address a non-normal event's sometimes stringent time requirements [19].

[7]Only includes the first data point

Etherington et al. [22], with the synoptics and shortened ECL approach, found comparable time reductions of 25% for a blocked pitot-static system scenario and 30% in a left hydraulic system failure scenario. Especially the latter would directly compare against the hydraulic leak failure. Interestingly, both proposed designs realised approximately 30% time reductions, despite the distinctively different approach taken. However, Etherington et al. indicated to have achieved a large variability in time reductions, whereas for this research, the time reductions appear to be relatively consistent. Additionally, when considering the net time to completion, the AECL slightly outperforms with 42% when compared against the ECL.
The percentage difference between both the gross and net values can be explained by, firstly, an arithmetic cause since time differences are now compared against a smaller absolute value. Secondly, AECL-using participants were more likely to perform concurrent processing of checklists. For example, a checklist may ask participants to wait for two minutes. In such a case, most participants chose to continue with another checklist, since automation would take care of the remaining to be automated steps. Unlike for the baseline, where the checklists were completed in isolation (not inside the menu), from which it was perhaps less stimulating to continue with another checklist. Other factors causing discrepancies could be, for example, the interrupting concurrent task.

Experienced workload was not significantly reduced as per the RSME measure. Also, the concurrent task scores do not indicate significant differences in dealing with competing tasks. However, following the discussion on the reduced AECL time requirements, it can be argued that a comparatively equal experienced workload is achieved for the AECL, but over a shorter time frame. Although the RSME scores do not support the hypothesis of a decreased experienced workload for the AECL, above explanation might hint towards an overall experienced workload reduction. This would require further experimentation and could be enforced by putting a higher time pressure on the participants.
Thomas [21] did show to achieve a lower experienced workload score for higher levels of automation. However, due to the lack of challenge in the scenario itself, the practical differences were considered minimal.

A risk of implementing automation is a lower situation awareness. Measurements of situation awareness did not find any significant impact, although it should be noted that median scores for the AECL are notably lower and of wider variability. Aforementioned situation awareness differences, after referring to participant commentary, are likely the consequence of a lack of automation feedback. Despite other literature highlighting its significance [36] [46], the decision was taken to minimise workload and time requirements. Although no significant effect was seen in situation awareness, the unanimous participant commentary invites further design development to support automation feedback.
Participants indicated that although they trusted the automation, they nonetheless frequently referred back to the overhead panel to find confirmation on their expectations of how exactly automation had changed the flight deck configuration. Trust in starting the automation process, however, was not an issue, likely due to the knowledge that higher authority steps are not automated and that pilots generally have a strong sense of checklist context. As such, for further improvements, it is proposed to feed back the final results of the automation attempt. This would also overcome the issue of obtaining a ponderous display due to the uncertainty of final switch positions, which are not foreknown and depend on conditional line items. In other words, in some cases, a multitude of options for just one switch has to be provided, which, depending on the conditional line item, might turn out to not even be relevant.
Likewise, the lack of automation feedback negatively affected acceptance scores. Nonetheless, an insignificantly higher median score of 8 out of 10 was achieved for the AECL, indicating participants accepted the AECL display but with room for improvement.

Little difference between the displays was observed in the decision-making outcome, hence, the choice of selecting the planned destination or the destination alternate. In the hydraulic leak failure scenario, participants for both displays took the most appropriate decision 67% of the time, since the planned destination is commercially most attractive and ample redundancy is in place. Furthermore, for both displays 33% of participants selected a far more risky approach by committing to destination alternate, where only one runway is available and other airports are unreachable with the now non-retractable landing gear.
For the drive shaft failure scenario, 83% for the ECL and 67% for the AECL followed checklist instructions rigorously on the basis of landing at the nearest airport, which is destination alternate. Nevertheless, the exact checklist instruction was to land at the nearest suitable airport, which in context of the flight plan is encapsulated by answering the question whether the aircraft is still authorised to fly RNAV approaches with an inoperative APU and under a drive shaft failure wherein due to an additional BTB switch malfunction, AC transfer bus 1 is lost. Despite that other research indicates a loss of AC transfer bus 1 and the APU inoperative no longer approves flying RNAV approaches [14], after careful joint review by a number of participants, not for all airline companies of which participant's volunteered the RNAV approach became unauthorised. For the other airline companies, RNAV approaches were not allowed. Notwithstanding, whether correctly diverting or not, in all cases the operational consideration whether RNAV approaches were still approved was none-existent to severely limited. Plausibly, this is due to the fact that checklists do not outline RNAV approach capabilities, rather, pilots are required to ascertain in a

proactive fashion whether such approaches are still approved. Similar findings of pilot unawareness of the RNAV approach with the same scenario were found in a study by Kramer et al. [14]. This calls into question the current NNC content which could benefit from better guidance on the technical feasibility of major flight components, such as approaches. To address this issue, an avenue worth exploring are ecological interface designs. This concern is however outside the scope of this research where checklist content is defined as a control variable.

Apart from decision-making outcomes, the time by which a decision was formed was significantly reduced with the AECL design, with 50.9% and 52.0% for median values for the drive shaft failure and hydraulic leak failure, respectively. First of all, such outcomes likely correlate to decreased time to completions for the ECL. Nonetheless, the much greater percentage time gain is surprising, since for example in the drive shaft failure, every participant started with a checklist that communicated to land at the nearest suitable airport. Therefore, all participants early on received this instruction, making the large difference in decision times surprising. Closer examination of video materials reveals that participants typically first consult more checklists before making a final decision, after inspection of critical elements such as fuel availability. An explanation could be that through automation participants have information available faster (lower times to completion) and only have to focus on directly relevant information, can thereby faster comprehend the situation, and hence subsequently form a decision. However, no significant evidence was found that supports or counters the second part of this interpretation.

Following the above discussion, the proposed AECL design delivers promising results. First, significant time reductions in checklist completion times (net time to completion) and decision-making were found, which would allow the pilot to better meet non-normal event time pressure [19] and deal with higher troubleshooting times found for SPO conditions [12]–[17]. Moreover, comparable experienced workload and situation awareness was observed, but the measurements were realised within a shorter time window. This could indicate a lower overall workload and faster development of situation awareness. Therefore, for future testing, it is proposed to introduce a failure for which participants experience a higher time pressure when solving a scenario. Another possibility would be to measure throughout each scenario run, but such measurements techniques can be intrusive and for that were avoided for this experiment.

Additionally, continued design iterations regarding the communication of automation outcomes are proposed. In doing so, it is expected that higher situation awareness scores and acceptance ratings can be achieved. It is, however, a trade-off in terms of time requirements as more information may slow down the operator. On the other hand, time may be gained, since, as observed for some participants during the experiment, less time is involved in verifying the flight deck on the results of automation.

Finally, other factors ignored in this experiment should be carefully evaluated, such as complacency [25]–[28], automation bias [29] [30], and skill degradation [31] [32].

VI. Conclusions

To better support pilots during non-normal event resolution tasks, this research proposed an automated Electronic Checklist (ECL) which was tested through a human-in-the-loop experiment against a reproduced Boeing 787 ECL with 12 commercial pilots when assuming the Boeing 737 systems and flight deck. Significant reductions in time requirements were found for both the tested scenarios, with 31.3% and 42.0% lower median checklist completion times and 50.9% and 52.0% lower median decision times for the drive shaft failure and hydraulic leak failure, respectively. Following this result, pilots would be better positioned during emergencies wherein speed and accuracy is of essence.

Experienced workload did not significantly differ but was for the new design compressed in a shorter time frame, indicating a potential to better match the many competing tasks onboard aircraft during non-normal situations. Despite adopting automation, no significant indications of adverse effects on situation awareness were found, supported by comparable decision-making outcomes between both designs. Although initial results are promising, participants unanimously indicated a need for more automation feedback. It is proposed for next design iterations to better communicate automation outcomes.

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II

Literature Review

Graded Under AE4020

2

State-of-the-Art Checklists in Aviation

The first chapter of this literature review will explore the use of checklists in aviation. The goal is to gain an understanding of how they are used and how they aid pilots in their goals. A special focus will be on Non-Normal Checklists (NNC)s and the current state-of-the-art Electronic Checklist (ECL) display of the Boeing 787, as per the research scope discussed in the Introduction.

First, the historical context and why checklists were introduced will be elaborated upon in section 2.1, followed by a discussion in section 2.2 on the development towards the current state-of-the-art ECL, the Boeing 787 ECL. Subsequently, in section 2.3, the Boeing 787 ECL itself is discussed and how it closely works together with other annunciation systems, such as the Engine-Indicating and Crew-Alerting System (EICAS). Thereafter, in section 2.4, an analysis will follow on what kind of steps and information is included in an NNC. Finally, this chapter is complemented with an overview of current research and iterations on the ECL in section 2.5 and section 2.6, respectively.

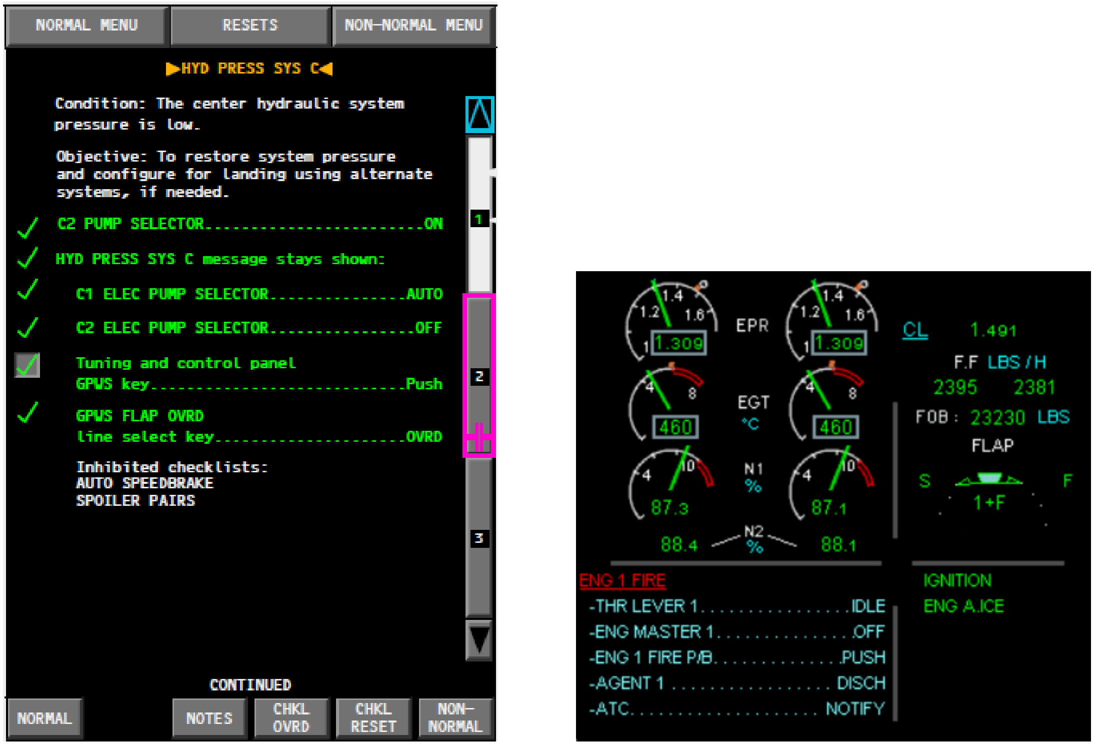
2.1. Checklists in Aviation

During a demonstration flight of a Boeing B-17 prototype in 1935, the aircraft fatally crashed shortly after take-off due to locked elevator and rudder controls [2]. It was the first aircraft that allowed for the locking of the controls from inside the cockpit, which, although being highly experienced, the flight crew failed to realise [3]. It was clear that aircraft operations became too complex for pilots to memorise completely and checklists soon became a mandatory item on aircraft. During World War Two, the B-17 flight manual stated that the checklist was "absolutely essential that the cockpit checklist be used properly by pilot and copilot at all times" as it was the "only sure safeguard" against pilot error [33].

Today, checklists serve as critical procedures to properly configure aircraft for all stages of flight [1]. Checklists can be divided into two domains: Normal Checklists (NC)s and NNCs [4]. NCs assist the flight crew to configure the aircraft before each phase of flight correctly. The NNCs facilitate the response to non-normal operating conditions, which can be a result of an inoperative, malfunctioning, or loss of one or more systems. Effectively, these checklists aim to correct, compensate for or otherwise accommodate for the non-normal condition [4] [5]. This research, as outlined in the Introduction, is concerned with evaluating NNCs, which, hereinafter, will receive the main focus.

2.2. The Evolution Towards the Electronic Checklist

Since the introduction of checklists, they have become customary onboard aircraft. For each aircraft type, all checklists are generally compiled into a Quick Reference Handbook (QRH), which serves as a manual for both NCs and NNCs. The QRH is brought aboard by the pilots as a hard copy. However, numerous issues are identified with traditional paper-based checklists [1] [4] [5]. In a study by Boeing [4] and others [6] in the 1980s, a vast amount of repeating human-induced checklist errors was found, which caused or contributed to accidents. In response, research was initiated to avert such errors by adopting a digitisation approach that led to the launch of the ECL program for the Boeing 777, which became certified in 1996 [7]. The evolution of checklists, from paper to digital, circumvents several paper-based checklist issues, including the difficulty of finding the



(a) (b)

Figure 2.1: The NNC representation as on the Boeing 787 ECL [8] in (a), and as part of ECAM in (b)

correct checklist, to keep track of where you are in the checklist, and to keep track of what is relevant later in the flight. A more comprehensive overview is presented in Table 2.1.

Today, the ECL is implemented on various Boeing aircraft, including the Boeing 787, Boeing 777, and Boeing 747-8 series. Similarly, the Airbus derivative, as part of the Electronic Centralised Aircraft Monitor (ECAM) system, is implemented in the A320 and A330 series, among others. The ECLs of both manufacturers are shown in Figure 2.1a and Figure 2.1b for the Boeing 787 and the Airbus 320, respectively. Both manufacturers, however, differ significantly in their approach. Boeing has a complete display dedicated to checklists and gives pilot flexibility on how to complete the checklists and in what order. Airbus, on the other hand, prescribes the next step to complete and the checklists are integrated on the ECAM display itself. Nonetheless, even when aircraft have the ECL, it is still mandatory to have the QRH present. The fundamental reason is that the ECL may become inoperative under certain system failures, and thus the hardcopy QRH functions as a safety net.

2.3. The State-of-the-Art ECL

The previous section highlighted the evolution towards the state-of-the-art Boeing 787 ECL. To build upon the previous section, this section elaborates on the workings of the Boeing 787 ECL. First, its function within the flight deck and the close connection with EICAS is discussed. After building a deeper understanding of the ECL's role and responsibilities, this section outlines how a pilot is expected to operate the display.

2.3.1. EICAS and the ECL

EICAS is an integrated system which provides the crew information on various instrumentation, such as engine parameters and fuel indications. The multiple functions of the EICAS display are organisationally visualised in Figure 2.2, whereas Figure 2.3 shows an example of how the engine, fuel and flap indication information is presented. Additionally, EICAS monitors whether the system state is as commanded by the pilot. When this is not the case, EICAS will alert the flight crew through a message on the display. Therefore, EICAS serves as the primary means to indicate non-normal conditions to the pilot. Following such a message, the pilot can now open the corresponding checklist on the ECL display. The EICAS messages appear in the right top corner (see Figure 2.2) and incoming messages are queued on their level of priority and recentness. Warning messages

Table 2.1: The problems of paper-based checklists and how they are addressed by the ECL (for the Boeing 777) [4]

Paper Checklist Problem	777 ECL Design Solution
Pilot must use one hand to hold the checklist	▪ Electronic display
List is cumbersome or difficult to read at night	▪ Electronic display
Pilot does not bother to run the checklist and does checklist from memory only	▪ Easy to access correct checklist ▪ Quicker to complete, requires less effort
It is difficult to distinguish between completed and noncompleted checklist items	▪ Checklist item turns green when complete (colour indicator) ▪ Checkmark next to completed item (graphic indicator)
Pilot can miss a step within a checklist	▪ Step remains incomplete (visually) ▪ There is no 'checklist complete' message at bottom of display ▪ After last page is completed, cursor and current line box jump to first incomplete item

Flying pilot does not know current progress within a checklist. "Where are we in the checklist?"	▪ Checklist is in view of both pilots
	▪ Current progress is indicated graphically:
	  ▪ Line item colour
	  ▪ Checkoff indicator/symbol
	  ▪ Current location
	  ▪ Page status indication

Pilot states that item is complete but fails to positively verify status of the item	▪ For sensed items, actual status indicated by colour, checkoff symbol, current line box, and cursor location
Pilot selects wrong switch by mistake	For sensed items: ▪ Display only responds to correct input ▪ Mistakes are readily apparent ▪ No 'checklist complete' message ▪ Cursor and current line box jump to incomplete item
Can lose your place when jumping from one checklist to another	▪ Automatic 'place holding' of last completed item when returning to any checklist
Pilot inappropriately continues with a checklist to prevent its interruptions	▪ Easy return to interrupted checklists (i.e., system stores incomplete checklists and last location within checklists)

It is difficult to know which non-normal checklists have been completed "Have we finished the checklist?"	▪ Checklist symbology next to EICAS message indicates completion status of non-normal checklist
	▪ Checklists are in view of both pilots with either:
	  ▪ Green 'checklist complete' message
	  ▪ White 'continue' message on bottom of each page

Pilot cannot find the checklist or selects the wrong checklist	▪ Checklist title same as alert message ▪ Correct checklist electronically linked to EICAS message ▪ When there are multiple problems, pilot presses one button to display a list of potential checklists correlated to EICAS messages ▪ Menu structure is arranged by subject (same as paper) ▪ Unannunciated checklists (i.e., with no associated message) can be listed more than once in menus
Pilot skips or forgets to complete a checklist	▪ Icon symbol remains in view to highlight checklists that are not completed ▪ 'NON-NORMAL' command button turns amber ▪ Selection of CHKL display select switch presents any unaccessed or unfinished checklists
Pilot goes down the wrong path in a branching checklist	▪ System senses 'conditional' statement when possible and shades out incorrect branch ▪ Cursor and next item box jump to next step
Pilot forgets to accomplish 'deferred' crew procedure steps	▪ Landing preparation items (ones to do later) are automatically attached to the approach or the landing checklist
Pilot forgets operational notes or limitations after a malfunction	▪ System automatically collects all notes for review at any time ▪ System associates notes and limitations by failure
Elapsed time evaluation is difficult (e.g., "After 30 seconds, select alternate bottle")	▪ Countdown timers are displayed on checklist ▪ Timers are automatically started

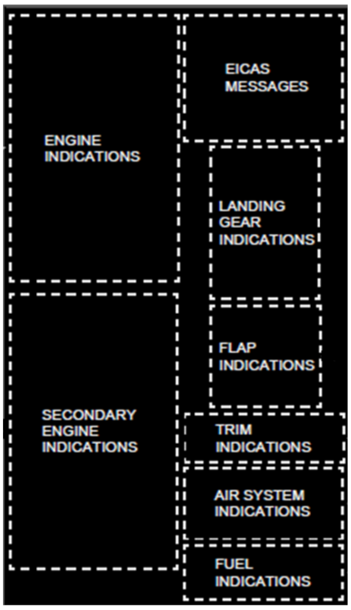


Figure 2.2: A schematic organisational overview of the EICAS display and its indications on the Boeing 787 [8]

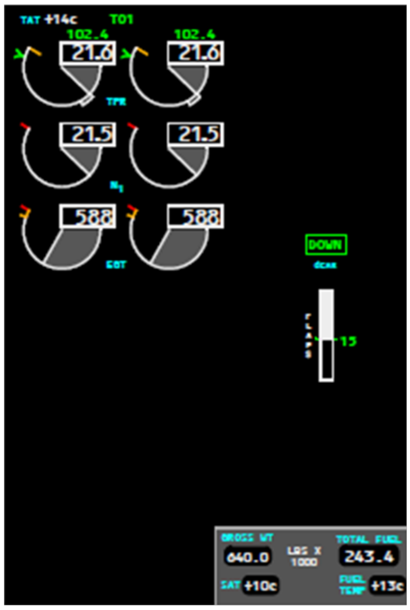


Figure 2.3: The Boeing 787 EICAS display showing engine, fuel, and flap indications during a hypothetical cruise situation [8]

are displayed in red and are the highest priority alert messages. Caution messages are the second highest priority messages and are indicated in orange, whereas the third and last group, the advisory messages, are also indicated in orange but can be distinguished by their indentation. Finally, there are also communication and memo messages which are displayed in white, although they do not have a direct relation to non-normal events and checklists. An example of EICAS messages is depicted in Figure 2.4. The white square icon in front of the warning message (FIRE ENG L) indicates that there is a checklist available that is still incomplete. Whenever the checklist is completed, the icon will disappear. Note that EICAS is not capable of detecting every possible malfunction. Consequently, not every checklist can be automatically displayed on the ECL. Such checklists are referred to as unanunciated NNCs, whereas checklists for which their underlying malfunction can be automatically detected by EICAS, are referred to as annunciated NNCs. Hereinafter, when referring to NNCs, it implies the annunciated version.

Checklists on the ECL display will be presented in the non-normal menu (see Figure 2.5), from which a pilot can open one of the NNCs presented (see Figure 2.1a) and start completing the checklist. The NNC titles, title colour, and order of the checklists are duplicates from the EICAS messages. Whenever only a single NNC is annunciated, the non-normal menu is not presented, rather the NNC itself is immediately opened by the ECL display.

2.3.2. Processing the Checklist

After selecting and opening the NNC from the non-normal checklist menu, the NNC at hand can be analysed and completed. This section aims to walk through the main elements of completing a checklist on the ECL display. First, the ECL display navigation functions are discussed followed by a detailed overview of the logic and content of an NNC.

The ECL display has an upper and lower menu, and a body of content. The upper menu bar can be used to navigate between the normal and non-normal menu, which list the relevant NCs and NNCs. Furthermore, a reset menu can be selected as well, from which both NCs and NNCs can be reset. Within the lower menu bar, on the bottom left, the NORMAL button can be pressed to go to the next active normal checklist (e.g., the approach NC when in cruise). Vice versa, the NON-NORMAL button can be selected to proceed to the next NNC in correspondence with the order of the EICAS messages. The remaining buttons on the lower menu bar are used to work through the checklist itself and will be discussed later on. Finally, when the total set of steps exceeds the space available on the ECL, additional pages are created, which can be navigated with the page bar on the right (see Figure 2.7).

Figure 2.4: Example of EICAS messages received on the Boeing 787 EICAS display. For the FIRE ENG L message, a warning, there is an uncompleted checklist associated with this message on the ECL. This is communicated through the white box in front of the message. For the ENG SHUTDOWN L (caution) and SPOILERS (advisory) messages, there are no active checklists. In total, there is space for 11 lines of EICAS messages available. When exceeded, a new page will be created. The current page is displayed on the bottom right, for this example that is page 1 (PG 1) [8]

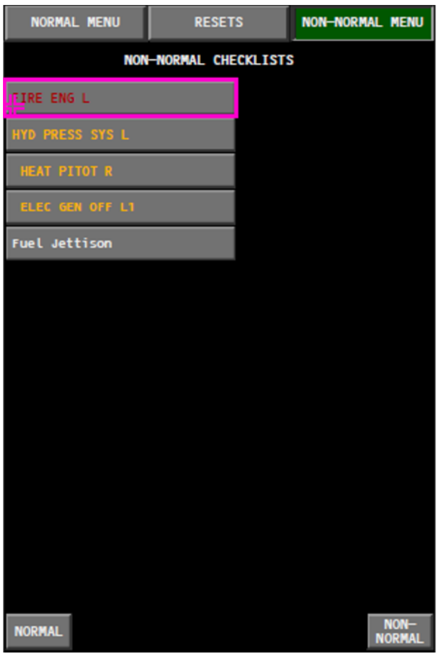


Figure 2.5: Non-normal checklist menu displayed on the Boeing 787 ECL display. Taking into account the level of priority and recentness, the pilot can from here select the next checklist to open [8]

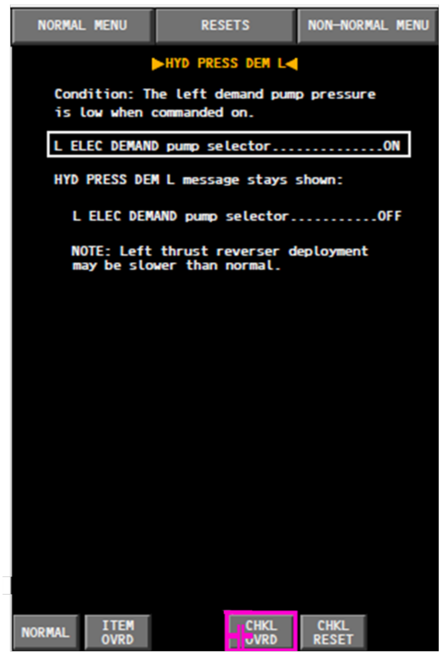


Figure 2.6: Example of a checklist presented on the Boeing 787 ECL [8]. The HYD PRESS DEM L checklist was opened from the non-normal menu displayed in Figure 2.5 [8]

Between the two menu bars, the actual NNC content is presented, which the pilot is expected to walk through in a sequential manner from top to bottom. On top, the checklist name is displayed in the colour of its level of priority, followed by the condition which triggered the checklist. Subsequently, the body of the checklist is shown in a list-type manner. Every step, or line item, requires the pilot to perform a particular action or provides relevant information about systems and operations. A more detailed overview of the each step type is provided in section 2.4.

Pilots can keep track of the checklist progress through text colours and the checkmarks in front of every checklist line item. Whenever a step is green, its status is completed and, when in white, the step is still incomplete. An example of a complete and incomplete step is depicted in Figure 2.7. Though, information-providing line items are also communicated to the pilot in white text. Since they solely provide information, there is nothing to complete, and hence, such line items do not hold a completion status. The next incomplete step – the current line item – is highlighted by an enclosing white box, to provide guidance on orderly completing checklists. The left side of a checklist line item indicates what element on the flight deck it concerns with, and on the right side, divided by a dotted line, the checklist states the desired state of this element. For example, in Figure 2.6, the pilot is tasked to set the L ELEC DEMAND pump selector to ON, which also is the active line item.

As part of a digitalised cockpit, the ECL utilises the power of recognising aircraft states. Therefore, if the desired state of a particular line item matches the state of the relevant flight deck item, the aircraft has the capability to automatically sense this and, subsequently, the step is displayed as complete on the ECL. As per the last example, whenever the pilot moves the L ELEC pump selector to ON, the checklist marks the step as complete. As discussed in section 2.2 (see Table 2.1 for a complete overview), this decreases human errors involving incorrect step execution, missing the step, or forgetting the step. Therefore, with the introduction of autosensing, the ECL will automatically detect whenever the relevant item is in the correct position and recognises the item as completed by making the text green and setting a checkmark in front of the line item. These sensible steps are called as closed loop line items. Open loop line items, on the other hand, cannot be automatically sensed by the aircraft and require the pilot to confirm and complete such steps manually. On the ECL, open loop line items can be recognised by the grey box in front, as shown in Figure 2.7. They can be manually checked by the pilot when the step is performed. After manually completing an open loop line item, the step turns green with a checkmark present in the grey box. An example of an open loop line item is shown in Figure 2.7

The pilot can also override items when, for a particular reason, it is believed they should not be completed at this very moment or at all. This is done by pressing the ITEM OVRD button in the bottom menu of the ECL, after which the relevant step will turn blue. Additionally, it is also possible to override the complete checklist by pressing CHKL OVRD. Similarly, a checklist can be reset by pressing CHKL RESET. Moreover, the ECL also automatically overrides steps during conditional line items. Such steps take an *if else* approach by selecting a certain branch of steps and automatically overriding the now superfluous set of steps (see Figure 2.23). Conditional line items are discussed in more detail in section 2.4.

On the bottom of the checklist (but above the bottom menu), the checklist status is displayed. When the checklist has multiple pages, of which one contains an incomplete item, the ECL will display 'CONTINUE' on the bottom, as can bee seen in Figure 2.7. At the same location, whenever the checklist is completed, a green box with the text 'CHECKLIST COMPLETE' appears, as depicted in Figure 2.8. When the checklist is complete except for the deferred line items (see section 2.4 for deferred line items), it will show the same green box but now it states 'CHECKLIST COMPLETE EXCEPT DEFERRED ITEMS'. Similarly, when the checklist is overridden in its entirety (by selecting the CHKL OVRD button), a blue box will appear at the same location which states 'CHECKLIST OVERRIDDEN'. Finally, whenever a checklist is completed which contained operational notes (see subsection 2.4.8 for an overview of operational notes), they are saved on a special page which can be accessed through the NOTES button on the lower menu bar. Therefore, throughout the remainder of the flight, pilots can easily refer back to said notes when deemed necessary.

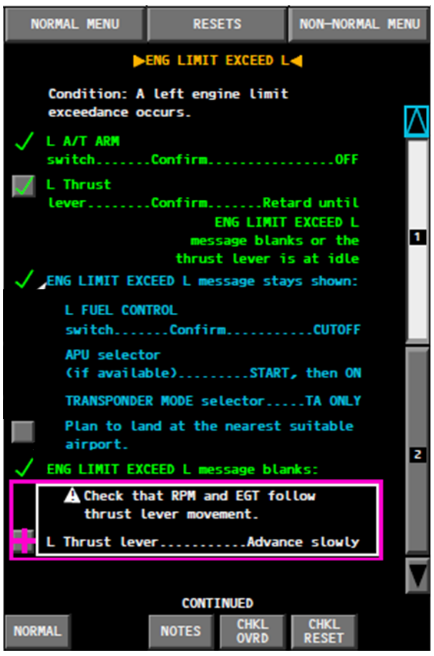


Figure 2.7: The steps in green and with a checkmark in front are completed. Blue line items are overridden and white line items are still incomplete or do not have a completion status (e.g., a condition or note). In this example, the bottom step, is the first next incomplete line item and thus the current line item. The current line item in this case is a open loop line item, recognisable by the grey box in front. To indicate to the ECL that the step is completed, the pilot can manually click the grey box with a cursor (displayed as a magenta cross) [8]

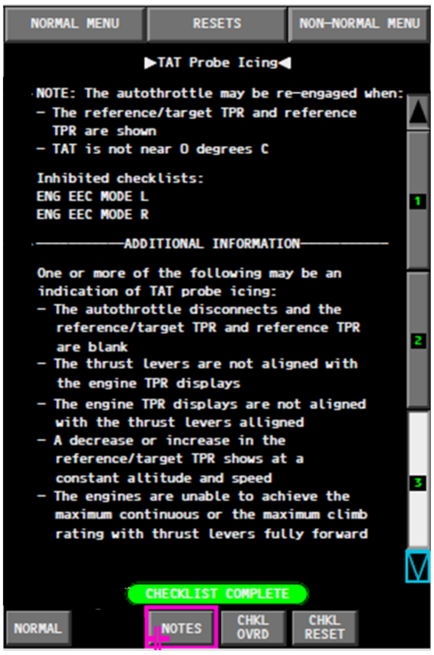


Figure 2.8: The checklist is compete, as indicated by the green box on the bottom of the checklist stating 'CHECKLIST COMPLETE' [8]

Figure 2.9: The CCD device lets the pilot control a cursor on various displays, including the ECL. The EFB and LWR button let the pilot select on which display the cursor is active (L and R lights annunciate where the cursor appears). Note that at all times the cursor is available for one display only. The cursor itself can be operated by moving one's finger over the touchpad surface. Lastly, the cursor select switch, on each side of the display, lets the pilot select menus, checklists, checklist steps (open loop line items), or other functions [8]

2.3.3. Cursor Control Device

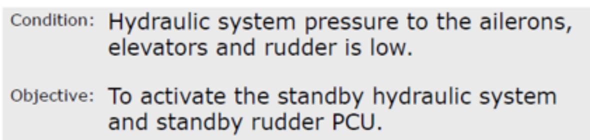
The ECL, as well as other displays, are operated by using a cursor, displayed as a magenta cross (see Figure 2.7), which can be used to navigate the menus and checklist pages. The cursor can be operated through a dedicated Cursor Control Device (CCD), located on both sides of the cockpit. Through a touchpad and selector buttons on both sides, the pilot can select menus, checklists, open loop line items, override and reset checklists, and perform other functions [8]. The CCD of the Boeing 787 is illustrated in Figure 2.9.

2.4. Step Types

Within NNCs, the type of steps to be undertaken by the pilot can be of varying nature. This section aims to break down the different step types, which is a central element in the design process to decide upon what steps potentially should or should not be automated.

2.4.1. Conditions and Objectives

On top of the checklist is the condition, which provides context to the pilot on why the checklist appears. Besides the condition, some checklists may contain an objective as well. An example of both a condition and an objective is shown in Figure 2.10. These types of steps merely provide information to the pilot and thus do not hold a completion status.


Condition: Hydraulic system pressure to the ailerons, elevators and rudder is low.

Objective: To activate the standby hydraulic system and standby rudder PCU.

Figure 2.10: Condition and objective for the flight control low pressure checklist from the Boeing 737 QRH [34]

2.4.2. Open Loop Line Items

Open loop line items, as defined in section 2.3, cannot be sensed by the aircraft. This type of step, therefore, always requires manual completion and confirmation by the pilot. Open loop line item can be manually confirmed as completed by checking the grey box on the left side of a step. When checking the grey box, the steps becomes green and a checkmark appears in the grey box. As such, whenever a checklist line item has a grey box in front, it is an open loop line item. An example of an open loop line item is shown in Figure 2.11 (note that the step is sourced from the QRH and thus has no grey box in front, please refer to Figure 2.7 for an open loop line item displayed on the ECL).

3 Establish crew communications.

Figure 2.11: Example of an open loop line item for the cargo door checklist from the Boeing 737 QRH [34]

2.4.3. Closed Loop Line Items

Closed loop line items, however, can be automatically sensed by the aircraft. In other words, it involves the continuous automatic monitoring of switch, lever, and selector positions [8]. Whenever the relevant line item matches the required position stated in the NNC, the ECL automatically recognises the step as completed and sets a checkmark in front of the step in addition to changing the line item's text colour from white to green. Within the sphere of closed loop line items, steps can be distinguished on their level of authority.

Switches and Selectors

Switches and selectors are used to manipulate the aircraft configuration. Switches, when movable in upwards and downwards direction, generally set a certain subsystem on or off. Some switches also have a neutral position. Furthermore, other switches are manipulable in a horizontal direction and thereby either select the left or right subsystem, or both, if the option is available. An illustrated example of a set of switches for the hydraulic pumps is shown in Figure 2.13. Conversely, selectors are rotational and give a multitude of options to select. In Figure 2.14, the R Wiper selector is shown as example. An example of the QRH instructing to move a closed loop line item is shown in Figure 2.12.

4 NOSE WHEEL STEERING switch . . . . ALT

Figure 2.12: Example closed loop line item of the loss of system A checklist from the Boeing 737 QRH [34]

Switches of Higher Authority

Some switches, however, require verbal confirmation from both pilots before moving the switch. Consequently, such steps can be categorised as higher authority. Whenever a checklist requires dual confirmation, this is indicated with 'Confirm' on the dotted line of the checklist step, as shown in Figure 2.15. The additional layer of safety comes from the level of impact of the switches on its own and other subsystems. They include an engine thrust lever, an engine start lever, an engine, APU, or cargo fire switch, a generator drive disconnect switch, an IRS mode selector when only one IRS has failed, and a flight control switch [35].

Guarded Switches

Guarded switches have even higher consequences to the aircraft's systems. Therefore, they have another built-in layer of safety. Before manipulating a guarded switch, not only both pilots have to verbally confirm on

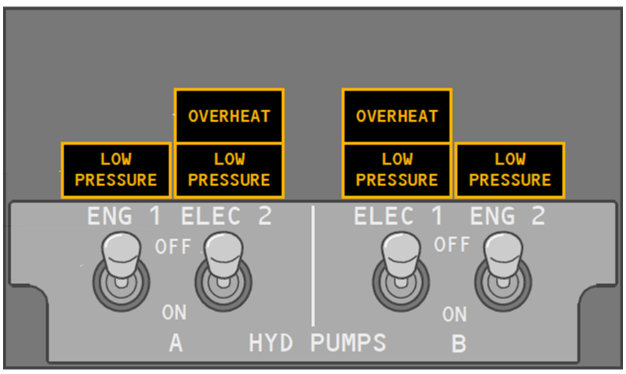


Figure 2.13: Hydraulic pump switches of the Boeing 737 [34]

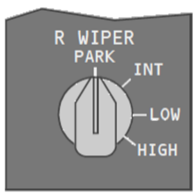


Figure 2.14: R Wiper selector of the Boeing 737 [34]

1 FLT CONTROL switch
(affected side) . . . . . . Confirm. . . . . .STBY RUD

Figure 2.15: Example of a closed loop line item where verbal confirmation from both pilots is required. The line item is of the loss of system a checklist from the Boeing 737 QRH [34]

performing the step, but also the guard protecting the switch has to be removed before it can be manipulated into certain positions. An example of a guarded switch is shown in Figure 2.17.
A special class of guarded switches are irreversible switches, which, once moved, permanently impact a certain aircraft system. Consequently, the system controlled by that switch is inoperative for the remainder of the flight and can only be reinstalled through servicing by maintenance. Irreversible switches are distinguishable from regular guarded switches due to the red colour of their guard (see Figure 2.17), whereas regular guarded switches have a black guard. An example of an irreversible line item is shown in Figure 2.16. The checklist step mentions the necessity of confirmation and the irreversibility explicitly.

Action is irreversible.
1 ⚠ Generator drive
DISCONNECT switch
(affected side) . . . . . Confirm . . . . Hold in the
DISCONNECT
position momentarily

This prevents generator drive damage.

Figure 2.16: Example of an irreversible step, where both verbal confirmation from both pilots is required and the guard has to be removed beforehand. Note that the step clearly indicates the action is irreversible through text and an exclamation mark. This irreversible step is part of the drive checklist from the Boeing 737 QRH [34]

2.4.4. Off Then On, and Duplicate Closed Loop Line Items

Some steps may ask the pilot to move a switch off and then on (see Figure 2.18). Therefore, within the same step, the switch at hand is successively in two different states. Generally, this step is applied as a quick reset. Similarly, the pilot may be asked to move the same closed loop switch into different positions on different occasions within the same checklist. The issue is that, due to autosensing, only one of the steps can hold the status complete, thereby compromising the completion of the checklist as a whole since it is now in a loop (it will go back to the first incomplete line item of the checklist). To overcome the problem, the previous 'duplicate' step(s) get automatically overridden once all prior steps are completed.

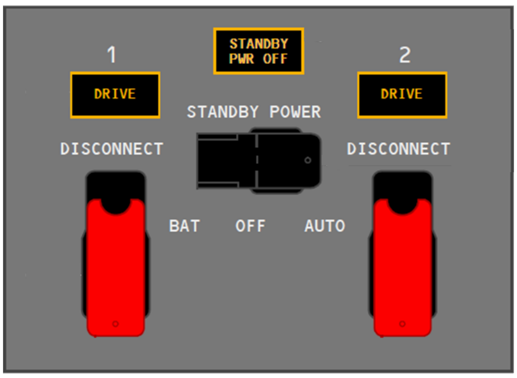


Figure 2.17: Example of two guarded (irreversible) switches on the Boeing 737 to disconnect the generator drive [34]

1 YAW DAMPER switch . . . . OFF then ON

Figure 2.18: Off then on step of the yaw damper checklist from the Boeing 737 QRH [34]

2.4.5. Timer Steps

Some checklist items may require some time before its result can be determined. Accordingly, the checklist will ask the flight crew to wait a certain amount of time before taking any further action related to the checklist (see Figure 2.19). The ECL will automatically start a timer on the top right of the display. In Figure 2.19, the current line item requires the crew to wait for 2 minutes with the timer indicating on the top right that still 1:23 of waiting time is left.

2 **Wait** 2 - 5 minutes.

Figure 2.19: Timer step of the window overheat checklist from the Boeing 737 QRH [34]

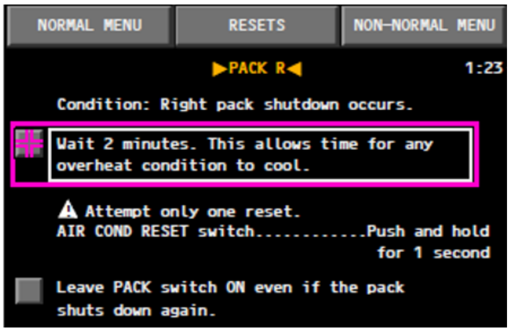


Figure 2.20: Example of a timer step as displayed on the ECL. On the top right it shows a timer indicating how long the pilot still has to wait, in this case 1 minute and 23 seconds [8]

2.4.6. Calculations

Non-normal events can cause systems to become inoperative or perform not to their required standards. Consequently, aircraft landing performance may deteriorate for which dedicated tables in the QRH can be addressed to realign expectations of the aircraft landing distance accordingly. For example, in Figure 2.21, the line item asks for recalculating the landing distance using a table such as in Figure 2.22. Based on the current checklist and the VREF setting (left column), adjustments are to be calculated for the aircraft landing weight, airport altitude, wind speed and direction, runway slope, and any approach speed adjustments.

3 Check the Non-Normal Configuration Landing Distance table in the Advisory Information section of the Performance Inflight chapter.

Figure 2.21: Example of a step asking to recalculate the aircraft landing distance in the loss of system A checklist from the Boeing 737 QRH [34]

		LANDING DISTANCE AND ADJUSTMENT (M)							
		REF DIST FOR 60000 KG LANDING WEIGHT	WT ADJ PER 5000 KG ABV/BLW 60000 KG	ALT ADJ PER 1000 FT STD/HIGH*	WIND ADJ PER 10 KTS		SLOPE ADJ PER 1%		APP SPD ADJ
LANDING CONFIGURATION	VREF				HEAD WIND	TAIL WIND	DOWN HILL	UP HILL	PER 10 KTS ABOVE VREF
ALL FLAPS UP	VREF40+55	1215	160/-75	25/60	-40	135	15	-10	80
ANTI SKID INOPERATIVE (FLAPS 40)	VREF40	1465	85/-90	40/50	-70	260	40	-35	110
HYDRAULICS - LOSS OF SYSTEM A (FLAPS 15)	VREF15	1000	70/-55	25/30	-35	120	10	-10	80
HYDRAULICS - LOSS OF SYSTEM A (FLAPS 30)	VREF30	965	65/-50	20/25	-35	115	10	-10	85
HYDRAULICS - LOSS OF SYSTEM A (FLAPS 40)	VREF40	925	55/-50	20/25	-35	115	10	-10	90
HYDRAULICS - LOSS OF SYSTEM B (FLAPS 15)	VREF15	1025	55/-55	25/30	-40	135	15	-15	75
HYDRAULICS - MANUAL REVERSION (LOSS OF BOTH SYSTEM A & B)	VREF15	1395	75/-80	35/45	-55	185	30	-30	145
LEADING EDGE FLAPS TRANSIT	VREF15+15	1020	75/-60	25/30	-35	120	10	-10	65
ONE ENGINE INOPERATIVE (FLAPS 15)	VREF15	920	65/-55	20/25	-35	115	10	-10	65
ONE ENGINE INOPERATIVE (FLAPS 30)**	VREF30	880	55/-50	20/25	-30	110	10	-10	65

Figure 2.22: Example of a landing table used to recalculate landing distances for a non-normal event. Above table assumes a dry runway and based on the checklist under consideration and the VREF, the row can be selected with which the calculations can be performed. Based on a reference distance at 60,000 KG, the pilot is required to incorporate adjustments for the aircraft landing weight, airport altitude, wind speed and direction, runway slope, and any approach speed adjustments [34]

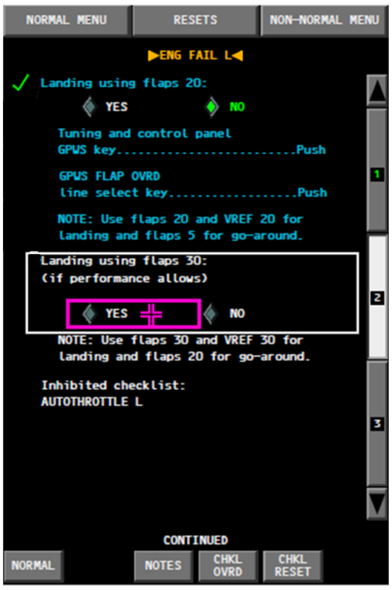


Figure 2.23: Example of a completed and an uncompleted conditional line item in the ENG FAIL L checklist. The completed closed loop conditional line item shows how now no longer relevant steps are overridden, whereas the uncompleted open loop conditional line item provides an example of how the pilot is required to select 'YES' or 'NO' in order to continue [8]

2.4.7. Conditional Line Items

This step, based on a particular condition to be met, takes an *if else* approach. They can be both open loop and closed loop and influence the continuation of a checklist by overriding the sequence of steps no longer relevant. An example is shown in Figure 2.23, where a set of steps is overridden because the condition of 'landing using flaps 20' is not met. The next step in Figure 2.23 is again a conditional line item, but this time an open loop version. The pilot has to verify the condition and can select 'YES' or 'NO' based on whether it holds or not.

2.4.8. Operational Notes

Operational notes provide operational information and limitations and are key for developing context and awareness of issues for later in the flight (example in Figure 2.24). Since this information may remain relevant for later stages of flight, a dedicated notes page can be selected on the lower menu bar, which collects and stores all notes per completed NNC. Operational notes, like conditions and objectives, share information and do not hold the status of complete or incomplete.

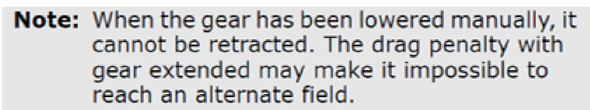


Figure 2.24: A note from the loss of system A checklist from the Boeing 737 QRH indicating that the now only manually extendable landing gear cannot be retracted once extended [34]

2.4.9. Deferred Line Items

Manipulating the flight deck results in a different state of the aircraft systems. Therefore, when completing NNCs, line items part of NCs may be affected. Whenever this is the case, the impacted normal line items are referred to as deferred line items. Deferred line items can change the action required to complete an NC step, add or replace an individual item, or introduce a new NC altogether. In the ECL, all deferred line items are automatically integrated into the NCs and also displayed at the end of the respective NNC. On the ECL, when an NNC is completed and has additional deferred line items, the ECL displays 'CHECKLIST COMPLETE EXCEPT DEFERRED ITEMS'.

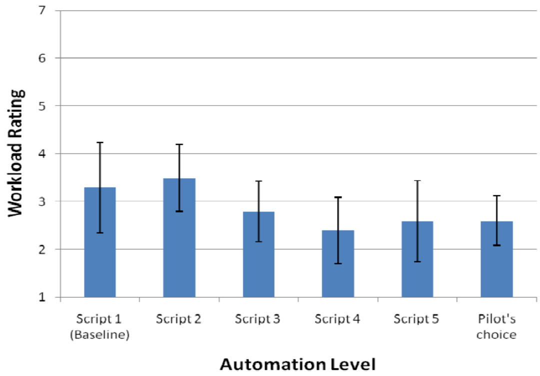


Figure 2.25: Workload ratings for the different levels of automation (on a 7-point AFFTC revised workload scale). Script 1 is no automation and script 5 is full automation [21]

2.5. Research on Improving the ECL

During this literature study, various studies have been identified that focus on improving ECLs. Proposed approaches range from automation to incorporating a synoptic display.

2.5.1. Automation of Memory Items Augmented with a Voice Interface

Research by Thomas [21] evaluated what level of automation was most appropriate in supporting pilots for non-normal event resolution tasks. The different levels of automation were augmented with varying types of voice messages (no messages, confirm each action, communicate intent and wait for confirmation, or communicate intent and act unless countermanded), with the objective to keep pilots in the loop to better support their situation awareness. Experiments were conducted with ten test and engineering pilots on a Boeing 787 virtual flight deck. One scenario was performed, which consisted of the first five memory items of the engine fire NNC. Additionally, participants were asked to manually control the aircraft to increase workload, although, in reality, such tasks would be split between the two pilots. Subjective workload ratings showed that pilot workload was reduced with automation, as can be seen in Figure 2.25. However, participants indicated the scenarios were completed “fairly easily”, resulting in little differences between the workload scores. Pilot preference indicated that intermediate automation was favoured with voice messages. Interestingly, pilots also indicated that full automation with no voice messages caused the pilots to be out of the loop. However, the study did not evaluate the performance of handling the scenario.

2.5.2. Combining the ECL with Synoptics

Etherington et al. [22] took a different approach by combining a newly developed synoptic display (SIS) and a simplified version of the ECL (sECL). Both displays were developed through a series of research and are presented in Figure 2.27. The objective of this study was to reduce the time required to get the aircraft in the correct configuration following a non-normal event and to have a greater understanding of the failure effects. In developing the SIS, new synoptic pages were created as well as enhancements to the current Boeing 787 synoptic pages were made. Consequently, checklists are reduced in length, since much of the checklist auxiliary information is now included in the SIS. For example, the unreliable airspeed checklist was reduced from six to three pages. It should be noted, however, that although checklist length is reduced, the information is still included in the synoptic display. Conceivably in a more efficient manner, but the net effect of text (or information) reduction is less than merely taking the gross cut in checklist pages. In this research’s series, experiments were conducted in a simulator reconfigured from a Boeing 757 to the Boeing 787 flight deck displays, interfaces, and functions.

Over the course of the research series, multiple scenarios were flown including a pitot and a hydraulic failure. The most recent experiment, AIME 2.5, made no direct comparisons against the baseline Boeing 787 ECL. However, AIME 2.5 did show a usability score increase from 70.4 to 85.5 on average for the Pilot Monitoring (PM) when compared against the SIS and sECL used in the penultimate AIME 2 experiment. The acceptability score, on the other hand, only saw a small gain. The usability and acceptance scores generated in the experiment are presented in Figure 2.28 and Figure 2.29, respectively.

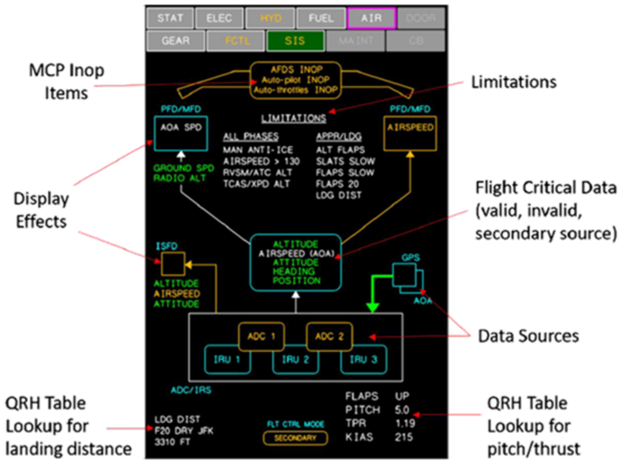


Figure 2.26: The SIS display of AIME 2.5 [22]

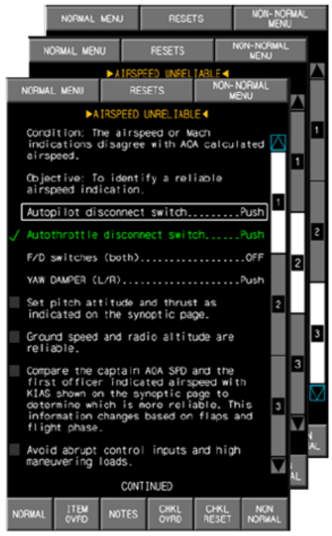


Figure 2.27: The sECL display of AIME 2.5 [22]

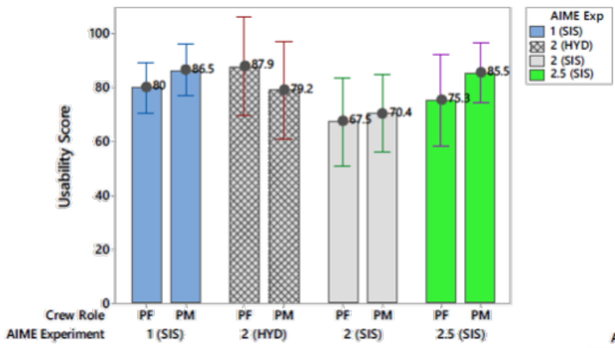


Figure 2.28: Post-run usability score for Pilot Flying and Pilot Monitoring across the AIME experiment series [22]

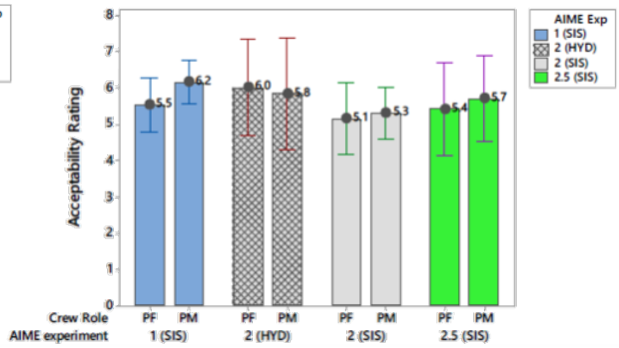


Figure 2.29: Post-run acceptability score for Pilot Flying and Pilot Monitoring across the AIME experiment series [22]

In the AIME 2 experiment, time savings were achieved of approximately 25% (mean time of 9 min 21 s) and approximately 30% (mean time of 8 min 57 s) for the blocked pitot-static and left hydraulic system failure, respectively, when compared against the baseline Boeing 787 ECL. It should be noted, however, that large variability was found in the completion times and that no statistical study was presented to support the results. Additionally, crew workload was reduced, and all pilots indicated that the tasks became less demanding. Notably, one pilot commented: "Increases SA significantly, and avoids PM becoming buried in long checklists".

2.5.3. Integrating the ECL into EICAS

A study by Li et al. [23] experimented with changing the setup for the ECL of a Boeing 777. Inspired by the Proximity Compatibility Principle [24], which states that related information should be in close spatial proximity, it was argued that checklist steps should be presented to the pilot within EICAS, as shown in Figure 2.30, and thus avoid the need to access the separate ECL display – a similar approach Airbus applies with ECAM. The proposed display is tested for four scenarios with 24 participants and compared to an electronic form of the QRH. The four scenarios used are a left engine fire (s1), a cabin altitude warning (s2), a right engine shutdown (s3), and a right engine generator failure (s4). The participants ranged between 0 and 3,000 flight hours, consisting of airline and non-airline pilots. Task completion time, as well as the time required to find the solutions to the failures, was significantly decreased when compared against the digital QRH [23]. The times of task completion for each scenario is shown in Figure 2.31. However, it should be noted that a more challenging comparison can be made when comparing the integrated EICAS approach with the current Boeing 777 ECL instead of the digital QRH.

Figure 2.30: Integrated design of checklist steps displayed within EICAS [23]

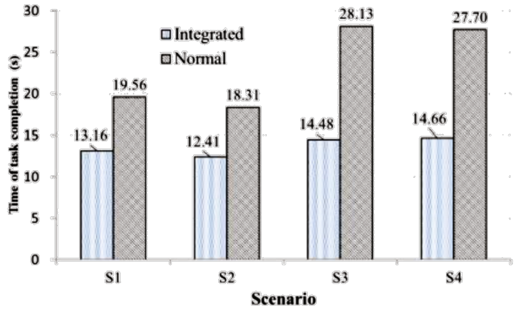


Figure 2.31: Time of task completion (s) over the four scenarios (s1-s4) for the integrated and digital QRH designs [23]

Figure 2.32: Manipulation of an ECL with the integrated touchscreen technology on the Boeing 777X

2.6. Current Developments of Hardware and Checklists

Although touchscreen technology already existed and had been commercialised, Apple's launch of the iPhone in 2007 transformed the manifestation of touchscreen interfaces all-around. Aircraft manufacturers have, however, been relatively slow in adopting the technology onboard. Although pilots bring aboard tablets to present maps and manuals or perform calculations, aircraft manufacturers only recently, or in the near future, started providing integrated touchscreen products for commercial aircraft. In December 2019, Airbus delivered the first aircraft with touchscreen cockpit displays on the A350. Specifically, the pilots can use the capability on the Electronic Flight Bag (EFB). Similarly, the Boeing 787 has touchscreen capabilities for its EFBs.

More significantly, Boeing undertakes a new step towards more extensive touchscreen integration for its new 777X series. The aircraft will be equipped with touchscreens for its forward flight displays, allowing for touch manipulation of interfaces such as the navigation display and the ECL, as shown in Figure 2.32. Another aircraft with broadly used touch-technology is the Gulfstream 650, which utilises a total of 13 touchscreens. As such, although very few commercial aircraft have integrated touch capabilities as of today, manufacturers seem to adopt the technology in its newest generations of aircraft.

3

Emergency Scenarios and Its Impact on the Flight Deck

In the Introduction it was highlighted that this thesis focuses on non-normal events. This chapter is aimed to analyse the inner nature, characteristics, and other factors of such events, especially since it directly influences the pilot's operations with the ECL and NNCs.
Non-normal events, or emergency-like situations, can bring a considerable change in the cockpit dynamic. Depending on the failure, safety can be under immediate pressure and workload is typically unexpectedly increased by a significant margin. Therefore, it is vital to build a better understanding of the effects on pilots during such events and to understand what other factors influence and challenge the aircrew. Burian et al. [19] describes six inter-related factors that influence the manner in which emergency situations are handled:

- specific aspects of emergency or abnormal situations,
- training for emergency and abnormal situations,
- economic and regulatory pressures in aviation,
- human performance capabilities and limitations under high workload and stress,
- aircraft systems and automation, and
- philosophies and policies within the aviation industry.

This chapter will start with section 3.1 by highlighting some of the factors indicated above, specifically, the aspects of an abnormal situation, the impact of training, and aircraft systems and automation. Thereafter, section 3.2 is dedicated to the factor of human performance capabilities and limitations under high workload and stress. Finally, in section 3.3, the effects on the pilots are reviewed when reducing the number of pilots from two to one.

3.1. The Dimensions Influencing Emergency Situations

This section aims at breaking down the dimensions that influence aircrew responses during such events. The most influential dimensions include the level of risk and threat, speed by which the crew requires to respond, degree of complexity of the failure, whether a problem is isolated or is a multiple system failure, and the familiarity of the situation [19].

The level of risk and threat allows aircrew to prioritise and estimate to what degree safe and controlled flight can be maintained. Time criticality, unfortunately, further complicates this process. It indicates how fast an emergency requires to be responded to. In other words, does it need to be addressed immediately, or can it be put in the waiting room for now? And, when resolving the incident, how much time is available to deal with the emergency? The availability of time may be a prominent constraint, as can be seen in the Boeing 737-200 emergency scenario on April 28, 1988 [36]. A section of the fuselage separated shortly before landing and all attention was on landing the aircraft safely, forcing the crew to complete 17 checklists in a 13-minute timeframe, almost solely from memory. Only once during flight and once after landing, the crew referred to

Table 3.1: The type of emergency and how the emergency was handled [20]

	Textbook Emergency	Non-Textbook Emergency	Total
Handled Well	19	6	25
Not Handled Well	3	79	82
Total	22	85	107

the NNCs. Hence, time criticality in this scenario indicated the need for an immediate response and the time available was severely limited for executing the appropriate measures.

As previously mentioned, another point of consideration is the complexity of the emergency at hand. Some scenarios may be relatively straightforward and others more complex, like electrical failures. Furthermore, pilots can be challenged more strongly when multiple system failures co-occur or when failures reach beyond the scope of procedures and checklists available [19]. Furthermore, automation and interconnected systems further add to the system's overall complexity, and hence, handling the scenario becomes more challenging [37].

The familiarity of the situation is another significant dimension. Recognising non-normal events allows aircrew to respond coordinated with limited mistakes. Following research by Burian and Barshi [20], it was found that pilots handled emergency scenarios proportionately better when a such a scenario was previously experienced during training. The study analysed 107 reports, from which 22 were so-called textbook emergencies, and the remaining 85 were classified as non-textbook emergencies. Textbook emergencies refer to a scenario that was practised in a training environment. The results are summarised in Table 3.1, which shows an apparent discrepancy between both categories. For the textbook emergencies, 19 were considered to be handled well, compared to only 3 situations that were not handled well. On the other hand, only 6 out of 82 situations were handled well for the non-textbook scenarios, leaving 79 cases to be not handled well. This is found to be a recurring problem during aviation training where there is an emphasis on scenarios already, or partly known by pilots [38].

3.2. Human Performance When Exposed to Emergency Scenarios

Experiencing a non-normal event during flight may increase the workload and the stress levels onboard. Consequently, human performance can be significantly impaired; especially human cognitive processes are compromised when under threat, stress, time pressure, or an overload of essential tasks [19]. In extreme cases, even the most obvious actions can become illogical to the pilot [19]. Moreover, emergency events may have a lasting impact on the remainder of the flight. ASRS reports describe errors made *after* a non-normal event due to elevated stress levels, despite that the emergency situation was handled well [20].

Many effects on human performance arise when subject to acute stress and increased workload. Tunnelling can be described as the process which narrows human attention [39] (also a situation awareness compromising factor, see subsection 5.3.1), and results in the human only perceiving the most salient information or threatening cues [40]. As a result, the pilot is solely focusing on one display or indicator, thereby missing other relevant cues.
Anxiety is a human emotional state elicited from stress or high-pressure [41] and is a natural reaction to tasks where consequences of performance are severe, such as in aviation. More specifically, it is a reaction to the threat of physical harm or accomplishing the current goal [42][43]. Allsop and Gray [44] investigated the effects of anxiety in a flightpath following task. Results indicated increased dwells to the outside environment and an uptake of randomness in instrument scanning. The human emotional state is thus indispensable for adequate reactions to emergency scenarios. Decreased performance can be linked to the weakened cognitive system of the human, the working memory.

Working memory is an essential element of situation awareness, as described in subsection 5.2.6. However, emergencies can cause working memory capacity decrements. Effects are a decrease in length of time information can be held, impaired problem-solving abilities, and difficulty in performing complex calculations [45] [46]. Other consequences of impaired working memory affect human perception, such as missing important cues

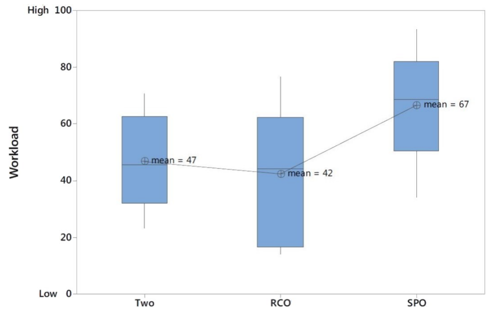


Figure 3.1: Workload for the drive shaft failure for the PF by crew configuration: Two, RCO, and SPO [15]

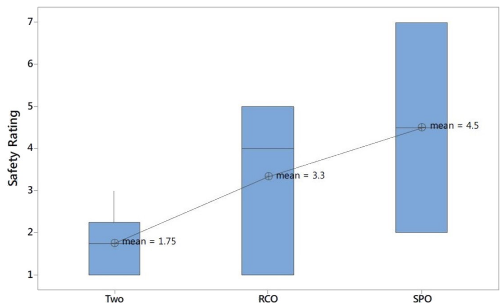


Figure 3.2: Safety rating for the drive shaft failure for the PF by crew configuration: Two, RCO, and SPO [15]

and finding and combining disparate pieces of information, particularly when information is incomplete, contradictory, or ambiguous [19]. Finally, with competing tasks present and increased time pressure, non-normal event resolution becomes more error-prone due to even more cognitive limitations [47].

3.3. Non-Normal Events with a Single Pilot

Manufacturers such as Airbus, Boeing, and Embraer and US Congress [10] have publicly indicated an active attempt towards realising Single Pilot Operations (SPO)s. However, a most likely bottleneck are non-normal events, as shown in a series of research by NASA [13–18].
In a Boeing 737-8 level D certified simulator, six non-normal events were evaluated:

- Unreliable Airspeed,
- Engine Fuel Leak,
- Reservoir Hydraulic Leak,
- Generator Drive Shaft Failure,
- Loss of Both Generators, and a
- Rudder Trim Runaway.

Each of the non-normal events was completed in a standard two-crew setup, a Reduced Crew Operations (RCO) setup, and a Single Pilot Operation (SPO) setup. With the RCO setup, one pilot was designated as resting pilot and could return to flying duties on request by the Pilot Flying (PF). However, this pilot wore a visual/audio restriction device and was isolated from both sights and sounds [14]. The overall conclusion of the research was that the participants indicated significantly higher workload and lower perceived safety for the SPO condition when compared against a two-member crew. Especially for SPO runs, workload-shedding of tasks took place, wherein among others checklist usage was sacrificed to attend other more vital tasks [14]. Also, performance deteriorated. For example, in the rudder trim runaway failure, time for troubleshooting increased fivefold and poor diversion decisions compromised flight safety under the SPO condition [18].

In this section, two of the evaluated failures are highlighted in more detail: the drive shaft failure and the hydraulic leak failure.

3.3.1. Drive Shaft Failure

Workload was measured with the NASA TLX, and although not significant, from Figure 3.1 it can be observed that for the SPO condition the subjective workload is clearly higher for the PF [15]. Breaking down the NASA TLX, which is a consolidated score over various dimensions, the physical TLX did show significance.

The perceived safety, a self-assessed measurement using a Likert scale from 1-7 (1: completely acceptable, 7: completely unacceptable), revealed significant crew complement differences for the PF [15]. From Figure 3.2, it can be observed that perceived safety worsens when going from a two member crew to a single member crew. The crew complement differences for the perceived safety of the PF were found to be significant.

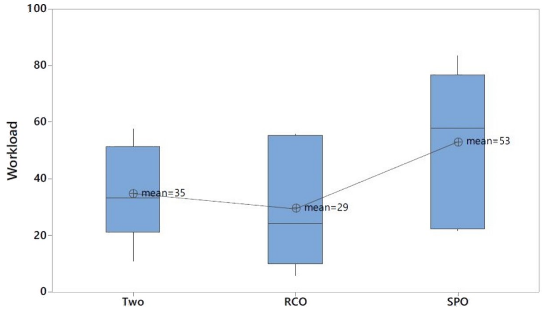


Figure 3.3: Workload for the hydraulic leak failure for the PF by crew configuration: Two, RCO, and SPO [16]

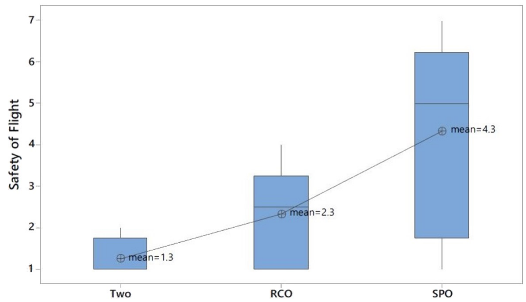


Figure 3.4: Safety rating for the hydraulic leak failure for the PF by crew configuration: Two, RCO, and SPO [16]

3.3.2. Hydraulic Leak Failure

Comparable results are found in the hydraulic leak failure, where data shows higher workloads and safety for the SPO condition [16]. Again, for the workload, no significance was found. But, similar to the drive shaft failure, when observing Figure 3.3 the data does show a higher mean for SPO conditions. Interestingly, the mean for the RCO is lower than for the two crew configuration, although it does suffer from larger variability. The paper did not discuss why the RCO experienced the lowest mean.

The perceived level of safety became unacceptable for the SPO condition, where participants struggled with combining tasks such as maintaining flightpath control, communicate with Air Traffic Control (ATC)/Dispatch, perform checklists, and manually lower the landing gear [16]. The lower experienced level of safety for the PF under the SPO condition can be clearly observed from Figure 3.4. In addition, also the statistical analysis revealed significance.

Checklist completion times did not show significance [16]. However, from the observed data, a higher mean and particularly a higher variability can be observed for the loss of system A checklist and the manual gear extension checklist, as shown in Figure 3.5 and Figure 3.6, respectively. Especially the variability under the SPO condition is a notable result, as some of the participants achieved a much higher checklist completion time. The researchers argue this is the result of a high workload and other competing tasks.

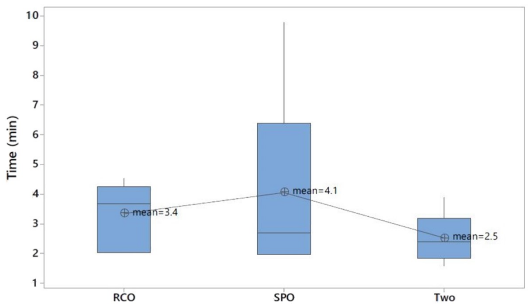


Figure 3.5: Checklist completion time for the loss of system A checklist by crew configuration: Two, RCO, and SPO [16]

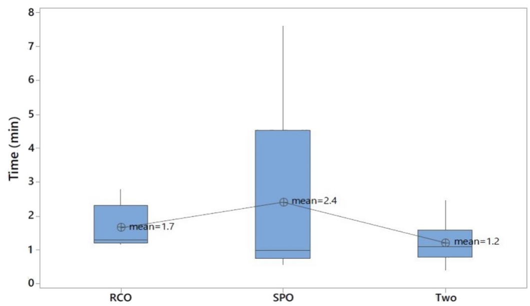


Figure 3.6: Checklist completion time for the manual gear extension checklist by crew configuration: Two, RCO, and SPO [16]

4
Automation

Since the beginning of flight, automation has played a central role in aviation. Already in 1912, the first aircraft autopilot was developed by Sperry Corporation which mechanically connected gyroscopes to the aircraft's flight control surfaces to maintain heading and altitude [48]. Two years later the autopilot was publicly demonstrated with a 'hands-free' flight in Paris, France. With the invention of the transistor in 1947 and the miniaturisation of computer equipment, aircraft adoption of automation technology soared since 1970 [49]. Since then, automated systems such as the Flight Management System (FMS), Traffic Collision Avoidance System (TCAS), and data processors like the Electronic Flight Instrument System (EFIS) display have become integral elements on the modern-day flightdeck. Over the past 50 years this resulted in a flight crew reduction from five[1] to two. However, newly automated systems are not always a definite success story, such as the now infamous Maneuvering Characteristics Augmentation System (MCAS) of the Boeing 737 MAX.
Automation is often-soughed after solution to increase productivity, efficiency, and quality control and to lower workload [50–52]. However, improper automation may lead to complacency, loss of vigilance, loss of situation awareness, confusion, skill degradation, and a higher perceived workload [25–28][31][32][49][53–57]. This chapter explores the benefits and drawbacks of automation and the various degrees in which automation can be applied.

First, in section 4.1, automation is defined and its benefits are elaborated upon. Section 4.2 examines potential automation drawbacks, whereas section 4.3 discusses the ironies involved when implementing an automation solution. After building an understanding of the implications of automation, its applications will be discussed. Section 4.4 outlines what classes of automation are available, followed by section 4.5, where the level of automation applied on such class(es) is discussed. In section 4.6, a flowchart for a automation adopting design is described, followed by a discussion on adaptable and adaptive automation in section 4.7. Finally, in section 4.8, an overview is presented of the various factors involved that influence automation use.

4.1. What Is Automation and Why Is It Desired?

Employing the Oxford English Dictionary, automation is defined as follows: "1. automatic control of the manufacture of a product through a number of successive stages; 2. the application of automatic control to any branch of industry or science; 3. by extension, the use of electronic or mechanical devices to replace human labour". In other words: "automation refers to the full or partial replacement of a function previously carried out by a human" [58].

Applying automation leads to many benefits across all industries, including aviation [25]. Advantages include reducing manual workload and fatigue, relief from small errors, economical utilisation of machines, precision in the handling of routine tasks, and increased capacity and productivity [50][52][57]. On the flight deck, the pilot extensively benefits from implemented automation with the autopilot, the FMS, and the flight director. However, it remains to be questioned if the overall workload and economic benefits are actually to be improved when taking into account automation disadvantages. The risks involved are discussed in the next two sections.

[1] Two pilots, flight engineer, navigator, and radio operator

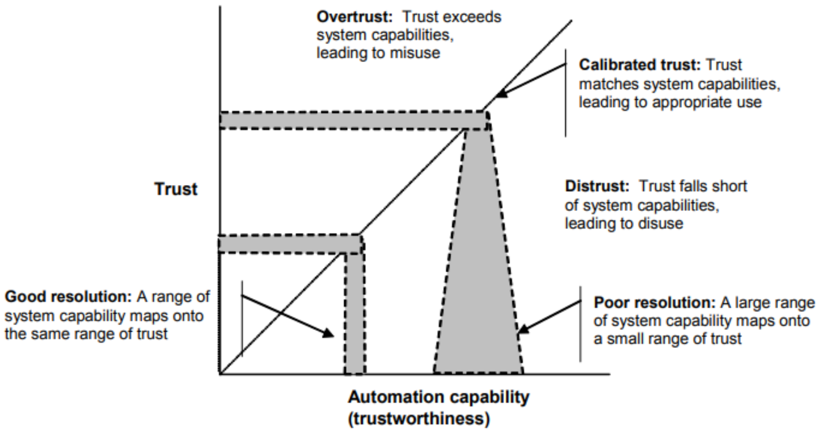


Figure 4.1: The relationship between automation capability and levels of trust [66]

4.2. Automation Drawbacks

Pilots have been pushed increasingly into a supervisory role on the flight deck [32][49][50][59], a result of the advancements in automation [60] [61]. Often reported issues in aviation associated with automation include complacency [26] [62], vigilance problems [53] [63] [64], skill degradation, and transient workload peaks [55][65].

4.2.1. Trust in Automation

The relationship between operator and machine is built on trust, which influences an operator's reliance on automaton [66]. A good calibration of the level of trust should match the system's capabilities and is elementary to avoid both under- and overreliance on automation (see Figure 4.1) [66]. Both extremes end in undesired scenarios. Underrelliance, or distrusting the automation, does not let the human operator fully capitalise on the system's capabilities. Trust requires acceptance of the technology and is gained over time through reliability and accuracy [50] [66]. Initial distrust is, for example, prevalent in safety-critical systems, such as with the Ground Proximity Warning System (GPWS), since the first versions were prone to false alarms [50]. Nonetheless, once good trust levels are developed, they may break down rapidly when violated [50].

On the other end of the spectrum is excessive trust; the operator becomes complacent with whatever the automation is doing. Complacency induced by automation describes the phenomenon of humans too heavily relying on automation, often unquestioningly so [25] [26]. Consequently, this may result in substandard monitoring of automation and its inputs and the acceptance of incorrect automation actions. In the context of autopilots, both forms (not monitoring automation and not overruling incorrect automation actions) of complacency have resulted in crashes. On Eastern flight 401, the crew failed to realise the autopilot disengaged, resulting in the aircraft crashing [67], whereas the pilots on the Airbus A320 of the Air Inter Flight 148 did not intervene while the engaged autopilot itself crashed the plane into the ground [68]. Evidence of complacency was also demonstrated in a study by Galster and Parasuraman [27], where pilots were less capable of detecting engine malfunctions using the automated EICAS system, instead of manually performing (and monitoring) the task. Pilots as a group may even be more sensitive to complacency effects. Riley [28] showed the reluctance of pilots to assume responsibility for the task in an experiment where the automation failed. Nearly half of the pilots did not turn off the automation, whereas, within the comparison group of participants, a group of students, almost every participant turned off the automation. Interestingly, the task was unrelated to aviation.

Closely intertwined with complacency is automation bias, a side effect of automated decision aids such as TCAS, GPWS, and the annunciation system of checklists found in EICAS and ECAM. Defined by Mosier and Skitka [30] "as a heuristic replacement for vigilant information seeking and processing", it leads to overemphasis on the automation generated advice whilst downplaying all other available advice [29]. Two types of errors exist, an error of omission – the operator fails to address the alert function – and commission error, where the operator committedly follows the incorrect system recommendation. Three factors can be ascribed as the main contributor [29][30]. The first is the natural tendency of humans to follow the (cognitive) path of

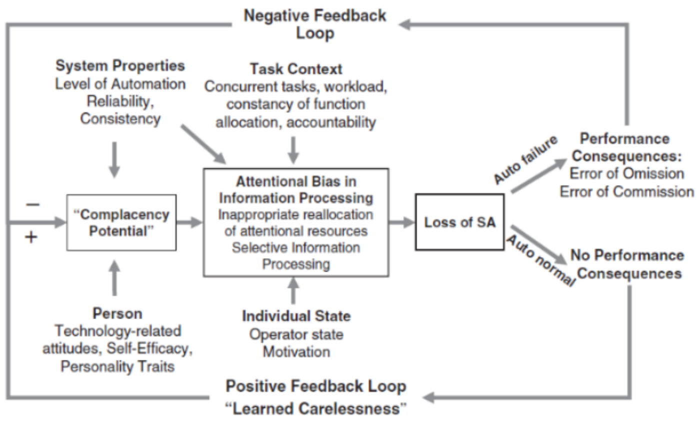


Figure 4.2: An integrated model of complacency and automaton bias [29]

least resistance [69]. A second factor is trusting automation in having superior analysis capabilities [66]. The final factor is 'social loafing', where humans exert less effort when working collectively instead of individually [70].

Parasuraman and Manzey [29] (see Figure 4.2) proposed an integrated model of complacency and automation bias. Complacency potential is considered the overall attentiveness of the operator towards the system, and the effects appear especially under high task loads. Errors of automation which are assumed to result in a loss of situation awareness, dynamically influence the complacency potential within the model. Depending on the performance consequences, the feedback is positive (no consequences) or negative (through error of omission or error of commission).

Trusting automation can also be forced upon an operator when experiencing high workloads, regardless of the level of trust [71]. In such situations, the operator has no other option than to rely on automation. Nevertheless, in the design of every automated system, the expected level of trust is to be carefully considered to avoid operators not accepting the new solution or becoming complacent and have automation bias, with all that this implies.

4.2.2. Vigilance, Skill Degradation, and Transient Workload Peaks

Vigilance refers to the ability to maintain focus and alertness over prolonged periods. It is a critical factor in human-machine systems as the human supervisor may be required to take responsibility during malfunctions or unusual events. With so-called vigilance decrements, humans may become inadequate in their responses, introducing the potential for accidents [54]. Furthermore, as pointed out by Bainbridge [32] (see subsection 4.3.1), deskilling can result in the pilot being less able to operate the malfunctioning aircraft during manual intervention [31].
Finally, one of automation's primary goals is workload reduction. However, 'clumsy' automation [55] addresses the paradox of an undesired redistribution of the workload when utilising automation, since it might lead to lower workloads during already low workload phases of flight, whereas during high workload phases such as landing, the overall workload increases [49][55].

4.3. Ironies of Automation

As already indicative from the previous section, considerable research is aimed at understanding the negative consequences of automation. Especially with regards to the collaboration of human and machine. This section discusses the "ironies of automation", following the identically named paper by Bainbridge. The paper discusses the ironies involved when designing and implementing automation. To expand, in a more modern context, an extended version of Bainbridge's ironies will be discussed in subsection 4.3.2.

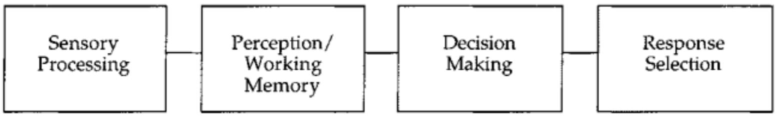


Figure 4.3: Simplified four-stage model of human information processing [74]

4.3.1. Bainbridge's Ironies of Automation

At first sight, automation looks promising but can be a pitfall when introduced, as described by Bainbridge in "Ironies of Automation" [32]. The paper addresses five fundamental reasons why automation can cause harm to the overall system. The first two ironies rest on the assumption of the designer, who assumes the human operator to be unreliable and inefficient and is to be eliminated from the system. However, errors in the design can cause significant operational issues. The second irony is that what the designer cannot automate is still left to the human. Another irony is the deskilling of humans when utilising automation. When a particular task is automated, the human will build less experience developing the skills necessary for this task —- ultimately resulting in skill deterioration. Building upon the latter irony, when automation is not working as anticipated, manual intervention is required. However, such events are frequently unanticipated and require even more skill of the operator. The combination of these two ironies invites drastic consequences whenever advanced skills are needed from the operator.

Incorporating automation pushes the human into a supervisory role. However, humans are not reliable performers for monitoring tasks. Humans are unable to maintain visual attention to a source when there is little action for longer than 30 minutes [72]; a phenomenon called the vigilance decrement (see subsection 4.2.2). The irony is that humans are now pushed into a position where it underperforms. Monitoring tasks introduces even more problems. For effective monitoring, the operator requires specialised knowledge which can be achieved through either dedicated training or the introduction of new displays aiding the monitoring effort. The second issue is that systems process knowledge much faster than humans, which makes monitoring all the available information impossible. Instead, monitoring is only possible at higher levels of abstraction. Again, this requires knowledge about the overall system in order to understand the underlying when solely observing the higher level of abstraction. Finally, it does not help the pilot that, through automation, the system itself is now inherently more complex than without automation.

4.3.2. More Ironies of Automation

Despite the paper being published in 1983, no fitting all-encompassing solution has been found for Bainbridge's "Ironies of Automation", as indicated by Strauch in a detailed review [73]. Instead, the increasing adoption of automation and the eruption of new technologies introduced new ironies [73]. Automation enhances system performance through increased reliability and accuracy. As a result, this may disguise operator performance shortcomings. Additionally, with complex systems, even small anomalies might result in severe consequences through interaction with the automation. Finally, the third irony states that repeated exposure to human-automation interaction errors not necessarily resolves the underlying cause.

4.4. What to Automate?

Following discussions on the benefits and pitfalls of automation, the question can be raised on identifying what to automate. A simplified four-stage model of human information processing (see Figure 4.3) can be applied as guideline of what classes of automation are available [74]. These classes, adjusted to system functions, are, in order of enumeration:

1. information acquisition,
2. information analysis,
3. decision and action selection, and
4. action implementation.

Automation can be adopted in one or more of the classes presented above. Acquisition automation relates to acquiring and registering data automatically; effectively supporting the human sensory process. The second step is information analysis, which refers to human processes such as working memory and interference.

Low	1	The computer offers no assistance, human must take all decisions and actions
	2	The computer offers a complete set of decision/action alternatives, or
	3	Narrows the selection down to a few, or
	4	Suggests one alternative, and
	5	Executes that suggestion if the human approves, or
	6	Allows the human a restricted veto time before automatic execution
	7	Executes automatically, then necessarily informs the human, and
	8	Informs the human only if asked, or
	9	Informs the human only if it, the computer, decides to
High	10	The computer decides everything, acts autonomously, ignores the human

Figure 4.4: Sheridan and Verplank's Level of Automation taxonomy [75]

Level of Automation		Roles: Human	Roles: System
None	1	Decide, Act	——
Decison Support	2	Decide, Act	Suggest
Consentual AI	3	Concur	Decide, Act
Monitored AI	4	Veto	Decide, Act
Full Automation	5	——	Decide, Act

Figure 4.5: Endsley and Kiris' Level of Automation taxonomy [76]

Automation in this class includes extrapolation for spotting trends as well as the integration of multiple input variables into a single variable. Decision automation – step three in the process – entails the selection of decision alternatives. Finally, action automation involves the execution of the action of choice. Automation would replace the actions conducted by a human, which generally are actions by voice or hands [74].

4.5. Level of Automation

After selecting the set of classes to be automated (see section 4.4) leads to the next step, which is to evaluate to what extent a particular class (or the system as a whole) should be automated. The degree by which a system is automated can be defined as the Level of Automation (LOA). The different automation levels consider the division of roles between human and machines, specifically in terms of autonomy – independence of a system to initiate and carry out automation – and authority, which denotes to the automation capability assigned to the system [31]. Establishing an appropriate LOA is vital since different levels are found to affect performance, workload (in NNC context [21]), and situation awareness [56].

Various proposals exist, with the LOA taxonomies of Sheridan and Verplank [75] and Endsley and Kiris [76] among the set of widely accepted frameworks. In Figure 4.4, Sheridan and Verplank's taxonomy is shown. The taxonomy divides over ten different levels from low to high levels of automation. Level 6 can be considered the buffer between either the human or the machine in control. Level 1, up to and including level 5, show the levels of automation where the human remains in control with the machine increasingly relieving the human of its responsibilities. Level 7, up to and including level 10, represent LOAs wherein the machine is in control, where level 10 fully excludes any human control over the system.
The LOA framework of Endsley and Kiris [76] contains five different levels of automation, with level 1 representing no automation and level 5 full automation. The framework, shown in Figure 4.5, has three inbetween levels wherein human and machine collaborate. Level 2 still has the human as ultimate controller with the automation merely providing suggestions, whereas level 3 and level 4 can be interpreted as management by consent and management by exception, respectively. Figure 4.6 shows an iterated version of [76] by Endsley and Kaber [77], where the LOAs are now broken down in ten levels. Also, an additional dimension is added by assessing the LOA per automation class: monitoring, generating, selecting, and implementation.
In a similar fashion, an additional dimension is added to Sheridan and Verplank's taxonomy [58]. Herein, the overall LOA of the complete system can be attributed to the various automation classes described in the previous section. Within each of these automation classes, the Sheridan and Verplanck LOA taxonomy is applied. An illustrative example is shown in Figure 4.7.

Levels of Automation	Roles			
	Monitoring	Generating	Selecting	Implementing
(1) Manual control	Human	Human	Human	Human
(2) Action support	Human/ computer	Human	Human	Human/ computer
(3) Batch processing	Human/ computer	Human	Human	Computer
(4) Shared control	Human/ computer	Human/ computer	Human	Human/ computer
(5) Decision support	Human/ computer	Human/ computer	Human	Computer
(6) Blended decision making	Human/ computer	Human/ computer	Human/ computer	Computer
(7) Rigid system	Human/ computer	Computer	Human	Computer
(8) Automated decision making	Human/ computer	Human/ computer	Computer	Computer
(9) Supervisory control	Human/ computer	Computer	Computer	Computer
(10) Full automation	Computer	Computer	Computer	Computer

Figure 4.6: Endsley and Kaber's Level of Automation taxonomy [77]

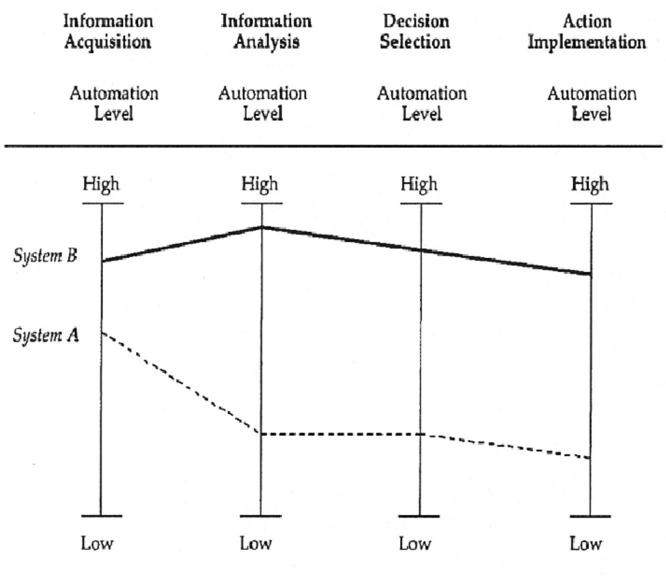


Figure 4.7: Sheridan and Verplank's Level of Automation taxonamy applied on the automation classes: information acquisition, information analysis, decision selection, and action implementation [58]

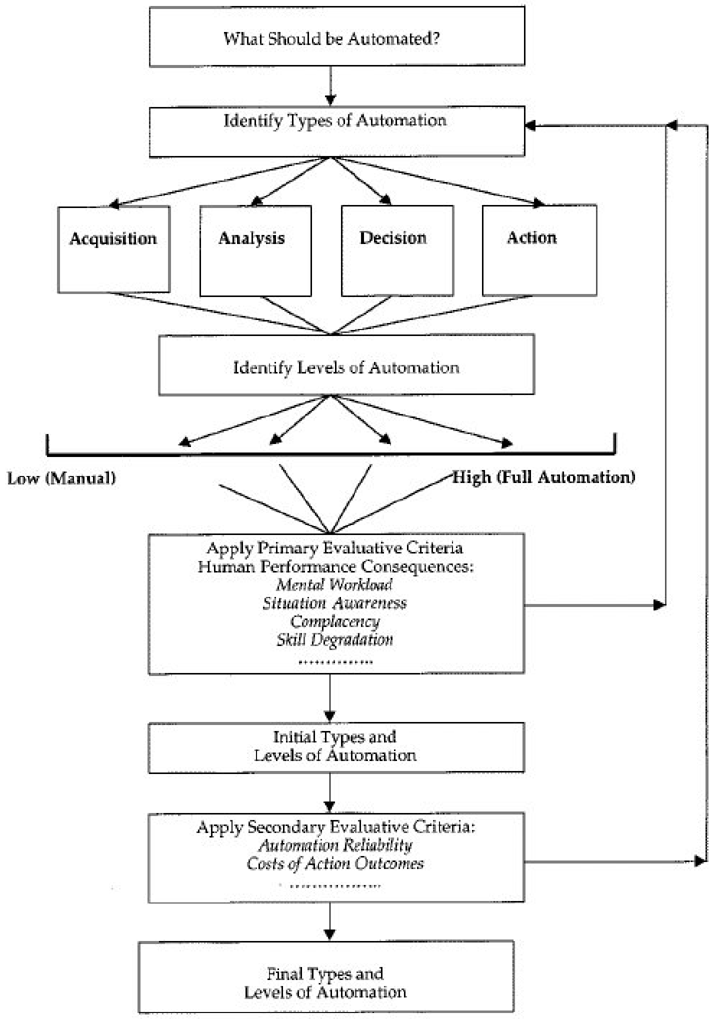


Figure 4.8: The flow chart describes the iterative process of first identifying what level of automation to apply on what automation class, followed by, first, a human performance feedback loop (includes criteria such as mental workload, situation awareness, complacency, and skill degradation) and finally by a secondary feedback loop (includes criteria such as automation reliability and costs of action outcomes) [74]

4.6. Designing for Automation

The automation concepts (automation risks, automation classes, and LOAs) described in the previous sections are, however, to be put into the context of a design process. A flowchart is presented in Figure 4.8, which describes the iterative process of evaluating the LOA per automation class for both primary and secondary evaluation criteria [74].

4.7. Adaptive and Adaptable Automation

The LOA framework describes the extent to which a system is automated, if at all, but seems to assume a fixed LOA post design phase across all operational situations. A fixed LOA can be referred to as *static* automation [78]. However, to what degree a system is automated is not necessarily of fixed nature. Depending on situational demands, control can be dynamically shifted between human and machine agents. In other words, after asking what to automate (automation classes) and how much to automate (LOA), the remaining question is when to automate, as illustrated in Figure 4.9. This can be realised through either adaptive or adaptable automation. Their distinction lies in the authority of dynamic function allocation. With adaptive automation, the automation itself is responsible for determining and implementing the function allocation, wherewith adaptable automation, the human bears this responsibility [79].

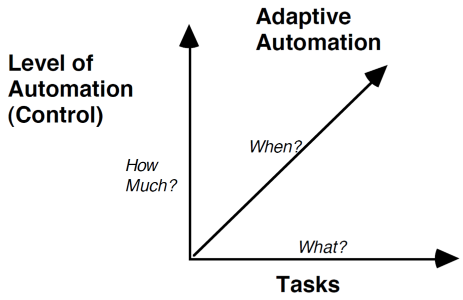


Figure 4.9: After answering what and how much to automate, the question of when to automate remains [80]

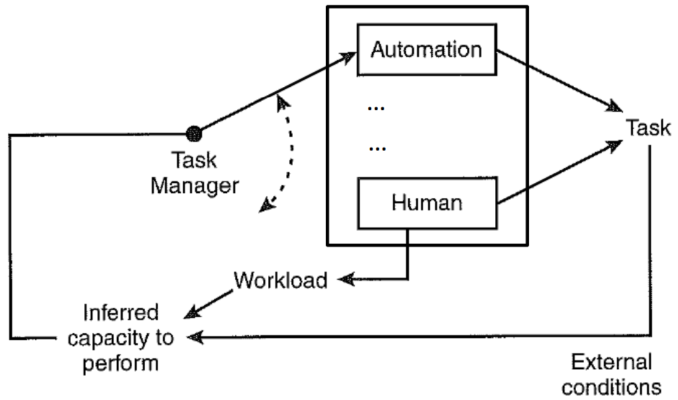


Figure 4.10: Concept of adaptive automation through workload measurements as driver for the task manager, which based on certain settings, allocates the task to the automation or the human operator [83]

Function allocation with adaptive automation can, for example, be performance-related. Deterioration of human performance, based on certain criteria, lets the system shift to a higher level of machine control. Similarly, physiological measurements can be utilised. When, for instance, an increase in workload is detected, the overall system may shift towards a higher LOA, as conceptually illustrated in Figure 4.10. Besides operator performance and physiological measurements, Parasuraman et al. [78] identified three more approaches: the critical events method, modelling, and a hybrid model of the aforementioned approaches. The critical events method [81] triggers the adaptive elements whenever an event occurs which directly influences system goals (i.e., a system malfunction). Finally, the modelling approach allocates functions based on a predetermined pattern of overall system functioning.

Nonetheless, each approach taken comes with its disadvantages. The critical event approach can advantageously be established during mission planning but ignores operator conditions. Operator performance and physiological measurements do take this into account, but how can performance be defined? Especially for more complex tasks, such as in aviation. Furthermore, it must be considered that any utilised physiological measurement requires careful consideration of their sensitivity and validity [25].

Adaptive automation, however, requires acceptance from the human operator, since the system is in control of giving and taking away tasks from the human. Moreover, fully adaptive systems may cause issues due to unpredictable behaviour of the user [82]. Such design issues can be mitigated by applying adaptable automation, wherein the human operator is responsible for dynamic task allocation. However, the drawback is that the act of delegation expands the set of tasks performed by the operator, thereby increasing the mental workload [25]. Invoking the automation can be achieved through a delegation interface which, when successfully designed, minimises the increase in workload, provides a flexible method of transferring autonomy, and communicates adequate feedback [25].

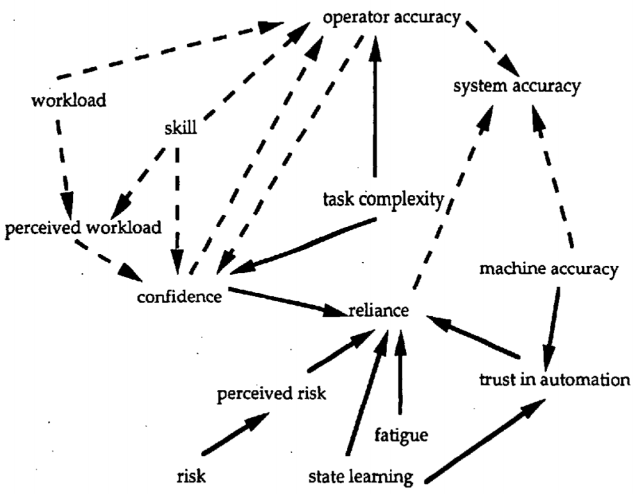


Figure 4.11: The web of factors influencing automation use. Solid arrows represent connections supported by experimental data, whereas the dashed lines indicated hypothesised relationships or connections that depend on the system at hand [84]

4.8. Choosing to or Not to Use Automation

Having an automated solution available does not necessarily result in the operator leveraging its capabilities. In an adaptable automation environment, the operator, after all, delegates task responsibilities. Riley [84] proposed a model of automation usage (see Figure 4.11), outlining the vast set of influencing factors and their interdependencies. Factors include task complexity, trust in the automation, automation reliability, risk, learning about automation states, operator confidence, and fatigue. The individual influence of each factor and their complex interactions remains highly subjective. Therefore, in a human-centred automation approach, the choice is at the operator's discretion [50]. The designer is left with the tedious task to project how operators will use the automation under specific circumstances.

5
Situation Awareness

From the beginning of human existence, awareness of cues in the environment – knowing what is going on around oneself – has been crucial. Ranging from hunts during prehistoric times to sports played today, good situation awareness increased chances of survival and success. Today, perhaps less critical for direct survival, situation awareness is nonetheless an essential factor for effectively performing tasks, since it is a crucial factor in decision-making, which is relevant to many disciplines such as sports, aviation, and medicine [85].
Pilots, in particular, control a complex system where operational safety is of the highest importance. It is of necessity to achieve a solid mental picture of various interrelated elements, such as flight conditions, location, aircraft configuration, and the aircraft energy state. This chapter's goal is to break down situation awareness in the context of a system operator. It is mainly of relevance due to its relation with automation and successful decision-making, which are vital elements of the design process in this research.

This chapter starts by defining situation awareness in section 5.1. Subsequently, a model of situation awareness in relation to decision-making and its key elements is outlined in section 5.2. Finally, this chapter concludes with a discussion on the dangers that can negatively affect situation awareness in section 5.3. This section is important in order to address and mitigate such factors during the design phase appropriately.

5.1. Defining Situation Awareness

Situation awareness is being aware of what is going on around you and how this impacts your goals. More specifically, in aviation, this allows for effective aircrew decision-making by being constantly aware of the ever-changing environment [57]. To maintain this awareness can be challenging, pilots are in an environment with many complex and dynamic systems and events. In combination with increasing technological advancements in aviation, where the pilot is pushed increasingly into a supervisory role, situation awareness has become a predominant design goal for interfaces and automation concepts [57].

Various definitions of situation awareness have been developed, refer to [86] for an extensive overview. For this research, Endsley's definition for situation awareness is assumed: "The perception of the elements in the environment within a volume of time and space, the comprehension for their meaning, and the projection of their status in the near future" [87]. The definition can be broken down into three separate levels [88]:

- Level 1: *perception* of the elements in the environment,
- Level 2: *comprehension* of the current situation, and
- Level 3: *projection* of future status.

5.2. A Model of Situation Awareness

This section further outlines Endsley's definition of situation awareness by breaking down all three levels described in the previous section. However, situation awareness is not an isolated phenomenon and is influenced by many factors, together forming the model of situation awareness during dynamic decision-making (see Figure 5.1). This section will elaborate on these factors as well, which can be categorised as either task/system factors or individual factors.

5.2.1. Level 1 Situation Awareness

The first level of situation awareness requires the perception of relevant elements. In the context of a pilot, this includes the monitoring of system status, warning lights, navigation, and even other aircraft. Formally described, level 1 situation awareness is to perceive status, attributes, and dynamics of such elements [89]. Various cues, such as visual, auditory, tactile, taste, or olfactory senses, may contribute to perceiving the information [57]. In a cockpit environment, level 1 situation awareness can be obtained through information from various displays, looking out the window, communication with other aircrew or ATC, other nonverbal communication, or vibrations from the aircraft itself [57].

For design matters, it is beneficial to identify issues that compromise level 1 situation awareness. Firstly, relevant information may not be perceived correctly, which can happen for various reasons. Data may never reach the aircrew through miscommunication, or there is a failure in the method of presenting, such as the malfunction of a display [57]. In other cases, the data is available but is not easily perceived. However, oftentimes the information is available and easily perceivable, but regardless the pilot fails to do so. Explanations include pilots simply not looking at the information or being occupied by other distractions [57]. Frequently, high workload demands are a major contributing factor to pilots not perceiving the available data [90]. Other sources for errors include misperception and memory loss. Misperception can be a consequence of assuming prior expectations and spatial disorientation, whereas memory loss refers to a pilot initially perceiving the information, but to subsequently forget it [90].

5.2.2. Level 2 Situation Awareness

After having perceived all relevant information correctly (level 1 situation awareness), the next step is to relate this to one's goals and objectives. Essentially, the pilot is required to take into account all the various disjoint elements of information from level 1 and compare this against the goals and objectives at hand – comprehending the information. Successful completion of this step forces the pilot to prioritise, integrate, and give meaning to many pieces of information to finally compare this against the goals set [57].

Errors in obtaining level 2 situation awareness refer to not comprehending the situation, which requires an understanding of the meaning and significance of the information [57]. The root of errors on this level often originate from having a poor mental model or not utilising the correct one. A poor mental model does not allow the pilot to associate perceived information with mission goals. Evidently, using a different mental model may lead to an incorrect evaluation and understanding of the situation. There may also be issues with an over-reliance on so-called default values in one's mental model [85]. Default values are expectations in the absence of real-time data, and hence, the wrong expectation about a system impairs the process of correctly comprehending the situation. Finally, there can be a misinterpretation of the significance of certain pieces of information, or not all information is adequately integrated when comprehending the situation [57][90].

5.2.3. Level 3 Situation Awareness

After perceiving all relevant information and successfully relating this to one's goals, level 3 situation awareness describes the pilot's ability to project this into the future [57]. For achieving level 3 situation awareness, it is a prerequisite to have both a good understanding of the situation and the system in question. In other words, this means that it is necessary to have a good mental model and the mental ability to project into the future constantly. Successful implementation results in being proactive and responding fast to events and to avoid adverse situations [57].

Level 3 can be argued as the ultimate level of situation awareness and often introduces many errors. Notably, a poor mental model will result in an erroneous future projection of the current situation. Other causes include putting too much weight on current trends or simply not having the required mental ability available since projection to a future instance is a demanding task [57][85][90].

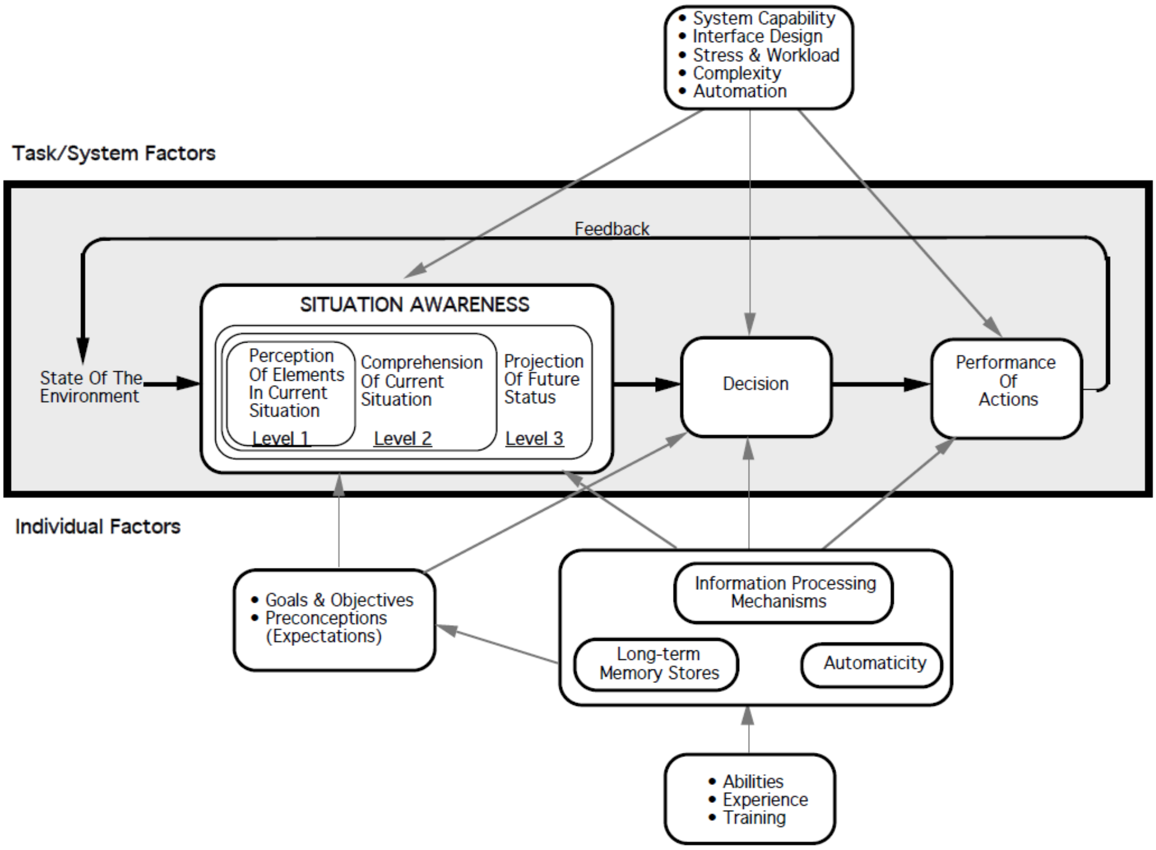


Figure 5.1: Situation Awareness model in dynamic decision-making [92]

5.2.4. Decision-Making

All three levels work together to obtain good situation awareness, with level 3 being the ultimate goal [57]. Particularly a good comprehension of the current situation is required to be able to project into the future, but this is only possible after having perceived all the relevant information. As such, the three levels are progressively interdependent. The three levels are visualised in a grander model in Figure 5.1, where also the interrelated nature of the three levels can be observed. Situation awareness directly drives decision-making and subsequently, the performance of the undertaken actions [91] (see Figure 5.1). The performance of actions serves as a feedback loop to the state of the environment, by which the process starts over again.

The model assumes a direct relationship between decision-making and situation awareness, however, having good situation awareness does not automatically lead to good decision-making [85]. It is thus possible to have good situation awareness but still make an incorrect decision. This is the direct result of multiple outside factors influencing situation awareness and decision-making, as depicted in Figure 5.1. The external factors can be divided over task/system factors and individual factors and are elaborated upon in the remainder of this section.

5.2.5. The Influence of Time on Situation Awareness

Time is a critical element in establishing situation awareness, and more specifically, the perception of time and associated temporal dynamics [88]. The perception of time means understanding how much time is available for a particular event to happen and before when action has to be undertaken [88]. Therefore, the perception of time is fundamental for developing good Level 2 and Level 3 situation awareness.

The associated temporal dynamics describe the rate of change of the information. This is crucial for projection tasks [87][92]. As such, for staying up to date, situation awareness has to be constantly changed in accordance with the dynamic developments of the environment.

5.2.6. Attention and Working Memory

Attention and working memory are human factors limiting the development of situation awareness. Attention will determine between various simultaneous and competing cues which one(s) will be processed and which are not. This is a function of two variables: the direction of a person's attention and the perceptual salience of environmental cues – the degree to which something draws attention [85]. How humans direct their attention is a result of various factors, including learned scan patterns, information sampling strategies, goals, expectations, and previously processed information [85]. The attention to the various information sources is prioritised based on perceived importance. This can be a demanding exercise, specifically for aircrew, who dynamically have to manage competing tasks and many pieces of information. Attention is a frequent cause of poor situation awareness development. In a research by Jones and Endsley [90], it was found that for approximately 35% of situation awareness errors, all the information was present, but not attended to accordingly. Causation of this error was most often due to competing tasks [90], which are of prominent presence on any modern-day flight deck.

The subsequent bottleneck of situation awareness is the working memory [87][93]. Working memory describes the limited human brain system that is responsible for dividing cognitive capacity between temporary storage and manipulation of the information [45]. Manipulation refers to processes such as combining, interpreting, and projecting information. Various studies researched to what degree working memory plays a role in developing situation awareness for different levels of expertise. It was found that especially novice decision-makers are more influenced by working memory limitations [94–96]. Experienced decision-makers apply strategies to reduce the working memory load, including information prioritisation, chunking, gistification of information, and restructuring the environment to provide external memory cues [97]. Regardless, an overload of information can still constrain experienced operators [98].

5.2.7. Long-Term Memory

Besides the working memory, humans can rely on another form of memory: the long-term memory, which benefits humans by working around the limitations of the working memory [92]. Various research describes the relation between the working memory and the long-term memory [97–100].

Part of the long-term memory are mental models. Mental models are a "systematic understanding of how something works" [92]. Having a (good) mental model helps to determine what information is important and to form expectations based on this information [88]. When fully developed, a mental model should provide the following:

- Dynamic direction of attention to critical environmental cues,
- Expectations regarding future states of the environment based on the projection mechanism of the model, and
- A direct, single-step link between recognised situation classifications and typical actions, enabling very rapid decisions to be made [88].

The third item describes a schema, which can be employed after recognising a specific situation. These situations are pre-known and let comprehension and projection to be obtained in one step [88], thereby providing a direct shortcut to develop situation awareness and circumvent loads on the working memory. Complementing a schema, are one or more associated scripts, which represent a sequence of actions to take. They are directly retrieved from memory and further limit the working memory load and support rapid decision-making [101]. With experience, pilots develop the long-term memory (mental models, schema, and scripts) to be a more efficient resource in supporting the working memory. Successful employment of mental models and its dependents hinges on the ability of a person to connect the environment to elements of the mental model [85].

5.2.8. Automaticity

Automaticity refers to both physical and mental tasks which, developed with experience, allow for the coupling of incoming cues with actions [102]. Hence, complete automaticity results in immediate situation awareness and decision-making. The better the automaticity, the less conscious attention is needed, which frees up mental resources. However, automaticity carries the risk of missing new information that falls outside the scope of the routine, thereby negatively impacting situation awareness [85].

5.2.9. Goals and Expectations

Humans alternate between two information processing strategies, goal-driven and data-driven. Goal-driven information processing lets the human focus on environmental cues that relate to one's active goals [57][92]. For example, when landing, it would be inefficient to pay attention to take-off specific indicators. Data-driven processing, on the other hand, is independent of a person's goals. It refers to the processing of information "based on the priority of its inherent perceptual characteristics" [57]. The efficient alternation between both methods is critical for situation awareness. Being stuck in goal-driven processing may result in missing other critical information, which ironically can result in improper goal selection. However, utilising only data-driven processing is highly inefficient and results in a higher workload [57].

In a likewise manner, having expectations can immediately direct attention to where it is needed [57]. Effectively, it functions as a mental shortcut and frees mental resources. Regardless, expectations also have drawbacks. Wrong expectations can cause one to miss relevant cues or to misinterpret data when trying to fit this to the wrong expectation [103–105].

5.3. Situation Awareness Demons

Several issues (or demons) come into play that may undermine building good situation awareness. Whenever situation awareness is an important element of a system to be operated, its design should carefully consider the situation awareness demons. The following situation awareness demons are identified [106].

- Attentional tunneling
- Requisite memory trap
- Workload, anxiety, fatigue, and other stressors
- Data overload
- Misplaced salience
- Complexity creep
- Errant mental models
- Out-of-the-loop syndrome

5.3.1. Attentional Tunneling

Attentional tunnelling refers to insufficient attention switching between different information sources [88]. As a result, relevant cues might be missed. The underlying cause is that, in case of an aircraft, the pilot believes the current attention-receiving source is the most critical or that pilots forget to scan other pieces of information. It is thus a necessity to keep a high-level understanding. For example, in 35% of aircraft and ATC failures, the needed information was present but not attended to [90]. Although the failure rate is dependent on multiple factors, generally, the operators are fixated on particular information sources, ignoring other task-relevant aspects, and hence have *tunnelled* their attention [106].

5.3.2. Requisite Memory Trap

As previously discussed in subsection 5.2.6, working memory is an essential factor in developing situation awareness, but has its limitations. A general rule of thumb is that a working memory cache can only consist of seven plus or minus two chunks of information [107]. This capability differs from person to person, but when exceeding this limit, the information will be lost. Additionally, over time the stored information decays, often rapidly so when not actively addressed [45]. This can occur in as quickly as 20 to 30 seconds [106]. Human ability, therefore, only allows a certain amount of storage of information for a certain amount of time.

5.3.3. Workload, Anxiety, Fatigue, and Other Stressors

Stressors, both mental and physical, can drastically impair working memory capabilities, thereby affecting situation awareness. Firstly, stressors can take up part of the working memory (see subsection 5.2.6) [106]. Secondly, when under stress, humans become less efficient at information gathering by being more disorganised, paying less attention to peripheral information, and become subject to attentional tunnelling (see subsection 5.3.1) [106]. Finally, stressors can cause premature closure, which refers to making one's conclusions without properly addressing all available information [106].

5.3.4. Data Overload

Data overload occurs when the rate at which data changes is too large for the human sensory and cognitive system to comprehend [106]. This results in a person's situation awareness to become quickly outdated and to contain gaps. Although the bottleneck lies with the human, data overload can often be seen as a design flaw [106], since the designer must be aware of human flaws.

5.3.5. Misplaced Salience

Misplaced salience refers to the issue that less important information draws more attention than the more critical information [106]. Salience is the 'compellingness' of information sources in the eye of the sensory system. As such, to draw more attention, colours, sounds, flashes, and others can be used to draw attention. Often defined by design, salience can be beneficial but has a dangerous downside of wrongfully drawing too much attention to less critical information [106].

5.3.6. Complexity Creep

The system complexity itself, as well as the number of systems involved, can slow down information intake and undermine correct interpretation and projection of the information [106]. Despite the system complexity itself, increased automation and displays can also increase the operational complexity, and hence, worsen the complexity creep. Automation adds to the complexity of the overall system, since it has to be understood how automation operates, under what conditions, and what other systems it influences, among others [106][108]. Similarly, for displays, their functioning has to be clear as well as how it impacts its underlying dependencies. For overcoming this issue, training and gaining experience are important [106].

5.3.7. Errant Mental Models

The mental model (discussed in subsection 5.2.7) can cause significant troubles to situation awareness when incorrect – as a critical interpretation mechanism, having an incorrect mental model results in inaccurate interpretations and projections (level 2 and level 3 situation awareness) [106]. Moreover, the wrong mental model can be selected, which are caused by mode errors. Mode errors let an operator to incorrectly assume to be in a particular mode (on which the mental model is based as well as schema and scripts) [106]. As a result, false assumptions about the current situation lead to poor situation awareness and thus decision-making.

5.3.8. Out-of-the-Loop Syndrome

A common negative result of automation is the out-of-the-loop syndrome. The syndrome occurs when there is poor awareness of the states of the controlled elements and of how the automation is performing [106]. Frequently, this issue is exposed when automation is no longer performing as intended. Effectively, during such an event, the system operator is often unable to detect the underlying issue, interpret the problem, and take action accordingly [106]. Endsley [106] proposed 'design principles' to address the out-of-the-loop syndrome:

- Automation should rather focus on routine tasks instead of higher-level cognitive tasks.
- Support situation awareness instead of providing decisions.
- Allow the operator to be in control and in the loop. The operator should understand what the automation is doing, how it is doing it, and what the next steps are.

III

The Automated Electronic Checklist Design

Graded Under AE4020

6

Design Background

NNCs provide system and operational information to the pilot and step-by-step instructions to configure the flight deck in accordance with the failure, to contain, isolate deteriorating systems, to restore system functionality, and to avoid any hazardous situations. Many of the steps require the pilot to move switches and selectors, which in ECL-equipped aircraft are tied to sensors. The sensible checklist steps, or closed loop line items, allow the aircraft to check whether the step is complete [8]. Therefore, closed loop line items would make excellent automation candidates. Automating closed loop line items would alleviate the mental and physical effort required, and consequently free cognitive resources to be concentrated on resolving the non-normal event or on other urgent tasks. Additionally, no attention shifting between different panels is required, displayed checklists are shorter, and automation has the potential to complete such tasks faster than humans. Integrating automation in the process of checklist completion would allow the ECL to better attest to non-normal situation's time pressure, spikes in workload, stress, and problem-solving needs [19][20]. However, as pointed out in chapter 4 and chapter 5, automation can be harmful to situation awareness. When the pilot becomes out-of-the-loop, one can actually expect worse decision-making and hence, non-normal event handling.
When looking back at the research question and objectives in the Introduction, the design goals are to lower workload and time requirements, and maintain situation awareness. Therefore, this chapter aims at connecting the literature review of part I with these design goals.

This chapter begins with a review in section 6.1 on how much of the Boeing 787 ECL is already automated. This is followed by a discussion in section 6.2 on why automation may be helpful to checklist completion tasks and section 6.3, which discusses the potential risks of automation in context with checklists. After that, in section 6.4, prior research on improving the ECL display is taken under the loop to evaluate what bits and pieces are promising to consolidate in this research's design. This is followed by a brief discussion in section 6.5 on why flexibility for the pilot is important in the context of non-normal events. Lastly, in section 6.6, the various types of checklist steps are discussed to identify which types make good automation candidates, followed by a brief summary of the design in section 6.7.

6.1. Connecting Automation and Checklists

Implementing an automated solution for handling checklists requires answers to the questions of what to automate, how much, and when [80]. What is automated can be categorised under four classes, which are based on a simplified four-stage model of human information processing and are adjusted to system functions (see Figure 6.1) [74].

ECLs already adopt automation within the first three classes. Acquiring information is automated where possible as the aircraft can detect malfunctions. Subsequently, information analysis is covered as well, since the

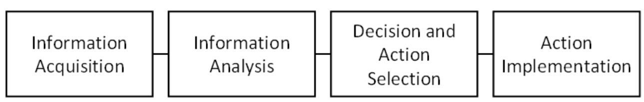


Figure 6.1: Four automation classes [74]

aircraft can integrate information input into a single or multiple EICAS messages with the associated checklists displayed on the ECL. Automatic generation of NNCs comprises decision and action selection as checklists are a script to get the aircraft in the correct configuration and provide supplementary information as well as flight continuation advice (e.g., divert to the nearest suitable airport, avoid icing condition, or limit flight altitude to a certain height). Note that, although it is generally advised against, pilots do have authority to override checklist steps and organise the checklist order at their priority. The action implementation – the execution of the checklist steps – is however still completely manual, although it should be noted that through autosensing the aircraft supervises the pilot's actions for closed loop line items. The proposed design focuses on automating the action implementation class.

6.2. What Is to Be Gained from Automating Action Implementation?

At first sight, automating action implementation seems to be a logical next step since, after all, checklists already prescribe the steps to be followed. Manually completing these steps takes effort and time from the pilot, two characteristics that are desired to be minimised during non-normal events (see chapter 3). It is hypothesised that when taking away this manual workload from the pilot, time is to be gained, workload is lowered, and the freed cognitive resources can be spent at analysing the situation at a higher level. Assuming the assumption perseveres, this would benefit the pilot's development of level 2 (comprehension of the current situation) and level 3 (projection of future status) situation awareness. Thereby, the chance of choosing the best course of action, or decision-making, is increased. Automation, however, may also have its pitfalls in terms of situation awareness and on other fronts.

6.3. Potential Risks of Automating Checklist Execution

Notwithstanding the potential gains, the implementation of checklist execution automation might jeopardise the pilot's situation awareness. Following Endley's model (see section 5.2), three levels of situation awareness are dependent on each other, and together form the pilot's situation awareness. Despite hypothesised potential gains in level 2 and level 3 situation awareness, they are directly dependent on a solid foundation, level 1 situation awareness.

Pilots may become out of the loop with the automation. As such, the understanding of and the ability to remember the current/correct configuration of the aircraft systems might be poorer (level 1 situation awareness). Moreover, although checklists directly prescribe actions, complacency can become an issue, especially during high workload situations where automation is an affordable way out. Although relatively rare, checklists are not necessarily to be followed by the dot and complacency in such a situation can result in an undesired outcome. Furthermore, complacency can cause a less than critical analysis of the information presented. Additionally, automation might hide pilot incompetence and result in the pilot becoming less knowledgeable and skilled with the flight deck.

6.4. Taking Inspiration from Fellow Research

To keep the pilot in the loop with automated execution of checklist 'memory items', Thomas [21] decided to use voice messages as a feedback mechanism. Pilots indicated a preference for such an approach and also indicated lower workloads for moderate to high levels of automation. Despite that no automation was applied, Etherington et al. [22] achieved to lower workload and the time required for checklist troubleshooting. This was achieved by shortening the checklist length and integrating this into newly developed synoptic displays. This demonstrated the benefits of more effective communication of the checklist information, stimulating the comprehension of the current situation (level 2 situation awareness). Similarly, through automation, checklist length can be reduced as these steps would become the responsibility of the automation. Therefore, not only performing the manual task itself is taken out of the equation, reading and comprehending this step is eliminated as well.

Another inspiration is taken from Li et al. [23], which integrated the ECL into EICAS, much like the ECAM system, under the proximity compatibility principle [24]. This research's newly proposed design does not follow this exact approach, but the above study did inspire the reassessment of when and where information is presented. Currently, NNCs are accessed through the ECL non-normal menu. And, once accessed, the pilot is inside the checklist. However, this means the operator is in isolation from all others. Taking into account that automation shortens the checklists, the new design proposes to present and complete NNCs from inside the non-norm menu, called the ‘dropdown’ menu. The dropdown menu only presents information directly relevant to the pilot (see section 7.2 for a detailed explenation of the dropdown menu).

6.5. Adaptivity

Due to the specific nature of non-normal events and the potential consequences involved, automated checklist execution shall be only set in motion at the pilot’s discretion. Hence, adaptive automation. To provide further adaptivity to the pilot, the complete checklist is still accessible as found on the state-of-the-art ECL (and thus not only the dropdown menu). This may in certain circumstances be beneficial to the pilot, in order to gain better context by reviewing the grander checklist. For example, a pilot may opt to review the deferred line items, which are not shown inside of the dropdown menu, but are shown in the complete checklist.

6.6. What to Automate?

For describing the LOA, various taxonomies exist [75–77]. The different automation levels consider the division of roles between human and machines, specifically in terms of autonomy – independence of a system to initiate and carry out automation – and authority, which denotes to the automation capability assigned to the system [31]. Establishing an appropriate LOA is vital since different levels are found to affect performance, workload (in NNC context [21]), and situation awareness [56]. Therefore, taking into consideration the effects of different levels of automation and the dynamics of non-normal events, different types of checklist steps are evaluated on automatability, situation awareness, time requirements, and authority for both upside and downside potential when deciding on what to automate.

First, the automatability of checklist steps is assessed. Open loop line items, by its very definition, cannot be automatically sensed by the aircraft and are therefore out of consideration. They require manual completion and confirmation by the pilot and can be recognised on the ECL by the grey box in front of a step (see Figure 1.1b). Furthermore, conditions, objectives, and operational notes do not hold a status of completion. Instead, they exclusively provide information. As such, since there is nothing to complete, there is no possibility of automation. Additionally, deferred line items are only to be completed whenever the NC becomes relevant, for example, the Approach NC. Consequently, they are not considered for automation.

Closed loop line items are autosensed by the aircraft and, when assuming the aircraft would be capable of moving switches and selectors, have the potential to be automated. Although automatable, the different types of closed loop step types are assessed if they should be automated.
The need for building situation awareness is already integrated within some of the checklist steps itself, as they can inherently differ in authority. Instructions for certain steps may indicate ‘Confirm’, which requires a verbal agreement of both pilots before action is taken [34]. Such steps, due to their respective impact, are classified as higher authority. They include an engine thrust lever, an engine start lever, an engine, APU, or cargo fire switch, a generator drive disconnect switch, an IRS mode selector when only one IRS has failed, and a flight control switch [34]. Within the class of confirmation-requiring steps, guarded switches are on the highest level of authority, since a guard protects switches before they can be moved into certain positions, in addition to the required verbal pilot agreement. Such is the case for, in example, irreversible steps, which, when effectuated, are permanent and can only be reinstalled through servicing by maintenance. Consequently, any step of higher authority is excluded from automated execution.

After evaluation of the other closed loop step types, no more were excluded for situation awareness or other concerns. These include conditional line items, off then on, and duplicate closed loop line item steps. Conditional line items take an *if else* approach wherein a set of now superfluous steps are overridden and can be both closed loop and open loop. When closed loop, the AECL automatically executes such a step. Off then on is a troubleshooting step by setting a switch off then on within the same step. Similarly, a duplicate closed loop line item requires the same switch to be in different positions within the same checklist. The issue is that, due to autosensing, only one of the steps can hold the status complete. Thereby checklist completion is compromised since it is now in a loop it will go back to the first incomplete step of the checklist). The ECL resolves this issue by automatically overriding the previous ‘duplicate’ step(s) once all previous steps are completed. The AECL will follow this logic as well and include closed loop duplicate line items in the automation attempt.

Table 6.1: Overview of what is automated and integrated in the dropdown menu by NNC step type

Step Type	Automated?	Dropdown Menu?
Condition & Objective	No	Yes
Regular Switch	Yes	No
Regular Selector	Yes	No
Open Loop Line Item	No	Yes
Confirm Line Item	No	Yes
Guarded Switch	No	Yes
Irreversible Switch	No	Yes
Timer	Yes	No
Calculation	Yes	Yes
Closed Loop Conditional Line Item	Yes	No
Off then On	Yes	No
Duplicate Closed Loop Line Item	Yes	No
Operational Note	No	Yes
Deferred Line Item	No	No

Some steps are rather time-consuming, such as calculation and timer steps. Non-normal events can cause system performance not to be up to par or the system to become inoperative, which in the case for landing-relevant systems (e.g., brakes and flaps) may increase the required landing distance. Pilots can address dedicated landing tables in the QRH to realign expectations of the aircraft landing distance accordingly. Such calculations are automatically performed with the AECL, which displays the output and output-yielding inputs (see Figure 7.1 for an example). Timer steps ask the pilot to wait for a certain amount of time (generally a few minutes) and are already automatically performed by the Boeing 787 ECL by displaying the time left. The AECL will also show the remaining time as well as integrating timer steps into the automation. An overview of all step types and whether they are automated is presented in Table 6.1.

6.7. What Will the Design Do and Not Do

This research's design adopts an automation approach for completing checklists during non-normal events. Any step with automation potential is taken away from the pilot as long as it is not an item of higher authority. This approach shortens checklists and frees the cognitive resources of the pilot by averting the physical and mental effort required when completing these steps. Instead, pilots focus on steps they are required to complete nonetheless (open loop line items and steps of higher authority) and any relevant information communicated to the pilot, including conditions, objectives, and operational notes. Finally, the pilot maintains flexibility on whether to use automation or not and to review the complete underlying checklist when deemed necessary.

7

Working Towards a Final Design

As explained in chapter 6, the goal of this research is to iterate on the current state-of-the-art ECL of the Boeing 787 to lower workload, enhance performance, and maintain situation awareness. The proposed solution is automation, which should relieve pilots from the physical and mental workload involved. Pilots are therefore only presented with tasks that cannot and should not be automated and with system and flight plan impacting information. This stimulates fast completion times of checklists and focuses the pilot's attention on important information, encouraging efficient use of cognitive resources. Building on those principles and goals, this chapter describes the proposed design.

First, in section 7.1, the annunciation process is covered followed by an overview of the dropdown menu in section 7.2. After that, in section 7.3, a detailed overview will be provided on how a pilot can perform automation with the AECL. This is followed by an explanation in section 7.4 on how pilots can process checklists and checklist steps concurrently and section 7.5, which explains how the lower menu bar works with the AECL design. This chapter concludes with a brief comparison between the AECL and the Boeing 787 ECL in section 7.6.

7.1. The Unchanged Annunciation Process

The relationship between EICAS, the ECL, and the annunciations remains unchanged for the new design. For that, the aircraft senses a malfunction of an aircraft system, the lights on the overhead or other panels illuminate (and in some cases a horn may sound), master caution illuminates, EICAS displays the corresponding message(s), and if relevant, the checklist(s) will show up in the AECL non-normal menu.

7.2. The Dropdown Menu

Inspired by Airbus' ECAM and the comparable ECL integrated into EICAS study by Li et al. [23], this research reassessed the location of checklist information presentation. Opting for a more integrated approach, checklists with the AECL can be processed from inside the checklist menu, instead of in isolation as is the case on the ECL.

Within the non-normal menu, checklists can be expanded and collapsed by pressing the right-side arrow button (see Figure 7.1). The expandable checklist is referred to as the dropdown menu, consisting of two main domains: the checklist content and a row from which automation and checklist progress is handled (see Figure 7.1). Presented content includes conditions, objectives, operational notes, open loop line items, closed loop steps of higher authority, and landing distance calculation output. Steps are included as they either present useful information or require pilot input in order to be completed. It excludes any automated steps and other non-relevant information to the pilot. The latter refers to steps overridden by conditional line items, which through an *if else* approach affects the continuation of a checklist by overriding the set of steps no longer relevant. As a result, some checklists on the ECL may appear relatively cluttered when compared against the AECL. Figure 7.2 depicts an example as a comparison between the reproduced Boeing 787 ECL and the AECL for the Source Off NNC.

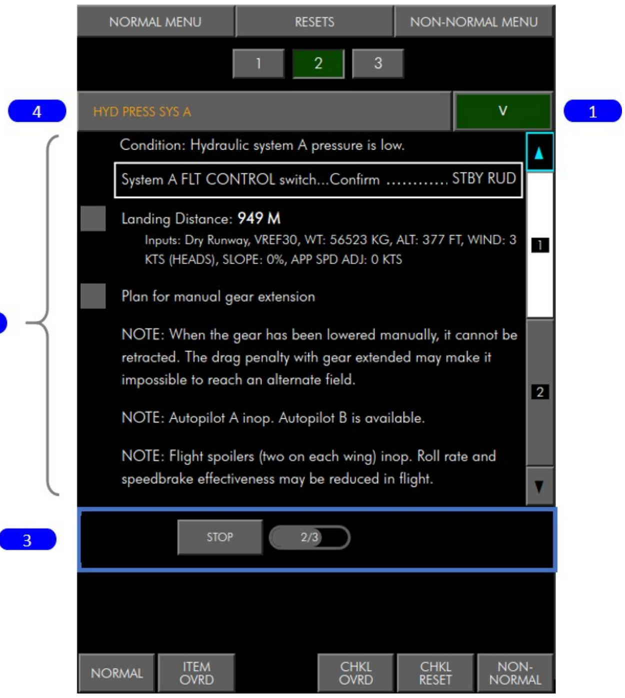


Figure 7.1: By pressing the arrow on the right-hand side **(1)**, the dropdown menu can be opened and closed. The dropdown menu itself consists of the reduced checklist content **(2)** and a row from which automation and checklist progress is controlled and supervised **(3)**. When deemed necessary, the complete checklist can be accessed by pressing the checklist name **(4)**, alike on the Boeing 787 ECL

To avoid displaying non-relevant information, the AECL dropdown menu dynamically updates when necessary after completing a conditional line item (an example is shown in Figure 7.3). The aim of the AECL is thus to present pertinent content only in a neat and efficient fashion. Nevertheless, the checklist as a whole is still accessible, like on the ECL, to provide flexibility since, depending on scenario circumstances and pilot knowledge and situation awareness, reviewing the grander checklist may be desired to gain further context (see Figure 7.1). For example, when the pilot would like to review the NNC's deferred line items, as they are not shared in the dropdown menu.

However, a checklist on the AECL might still exceed the maximum height of the designated area in which checklist content is presented. Similar to the state-of-the-art ECL, pagination on the right side allows the pilot to navigate multiple NNC pages. Similarly, if there are too many NNCs to fit into the AECL non-normal menu, a new page will be created. The non-normal menu pages can be navigated by the enumerated buttons in-between the upper bar and the NNCs.

7.3. Automating Checklists

Whenever a checklist contains automatable steps, the automation button can be pressed on the left to commence the automation (see Figure 7.3a). With automation in progress, the operator has the possibility to stop automation and is presented with an automation progress bar, which reports the fraction of the number of steps completed through automation divided by the total number of automatable steps (see Figure 7.3b). Once completed, the progress bar displays 'Done', as shown in Figure 7.3c. Additionally, from Figure 7.3c, it can also be observed that the checklist content was updated with two open loop line items due to a conditional line item (see Figure 7.3d for reference). After completing the remaining steps, the checklist displays its status of completion through the green bar stating 'Checklist Complete' (see Figure 7.3e). When the NNC has deferred line items, the green bar states 'Checklist Complete Except Deferred Items'. In case the user overrides the NNC, by pressing CHKL OVRD, a blue bar at the same location appears stating 'Checklist Overridden' Additionally, as shown in Figure 7.3f, the clear button on the right appears by which the operator can eliminate the checklist from the non-normal menu.

(a) ECL (1/2) (b) ECL (2/2) (c) AECL

Figure 7.2: The Source Off NNC displayed on the ECL is shown in **(a)** and **(b)** for page 1 and page 2, respectively. The non-relevant overridden steps are in blue and make the display relatively cluttered when compared against the AECL in **(c)**

The bar from which automation and checklist progress is handled and supervised (see **(3)** in Figure 7.1) works from left to right and can be categorised into three zones. In Figure 7.4, the three zones are indicated; however, note that the content of the zones not necessarily presented concurrently (see Figure 7.3 for the 'flow' of the buttons). The left zone controls the automation process. Here, the pilot can both start and stop automation. Note that when pressing stop, the AECL still finishes the current step. The middle zone shows the progress of automation and the checklists as a whole. Once the ECL is automatically completing the steps, the progress bar in grey (see Figure 7.4a) indicates the status of automation. Once every automation step is complete, the progress bar states 'Done'. On the right side of the progress bar, additional information can be displayed. For example, as can be seen in Figure 7.4a, a timer is shown. Once the checklists is completed (or overridden), the middle zone displays the status of completion with a green bar stating 'Checklist Complete' (see Figure 7.4b) or 'Checklist Complete Except Deferred Items', whichever is relevant. Also, when the the checklist is overridden, a blue bar with 'Checklist Overridden' is shown. Once the checklist is completed or overridden, the Clear button appears in the right zone, with which the checklist can be eliminated from the non-normal menu. The right zone is thus responsible for 'cleaning up' the non-normal menu.

7.4. Managing Multiple Non-Normal Checklists

Pilots are not withheld from processing multiple checklists simultaneously. Although not necessarily recommended since it contributes to errors from mixing up checklists and attention shifting, it can be a streamlined approach when, for example, a checklist asks to wait for two minutes. In the meantime, another checklist or task could be completed. Other reasons for opening multiple checklists may be to examine the content before actually executing the checklist. The non-normal menu can become disseminated over various pages with multiple checklists expanded; therefore, to avoid this issue, only one checklist can be expanded at all times. Accordingly, whenever the pilot expands a checklist, the others are collapsed.

Even within the same NNC, concurrent checklist handling is supported. When the AECL is automating, pilots are not withheld from completing any other step displayed in the AECL non-normal menu. This is possible since the menu only shows directly pertinent information and steps only. Therefore, the flow is organised in such a manner that pilots are not completing steps for which it later turns out that they should not have been completed (as is the case with conditional line items).

7.5. The Lower Menu Bar

The lower menu bars functions remain indifferent for the AECL. The buttons ITEM OVRD, CHKL OVRD, and CHKL RESET are actionable whenever a checklist is expanded. And hence, they are not operable when all

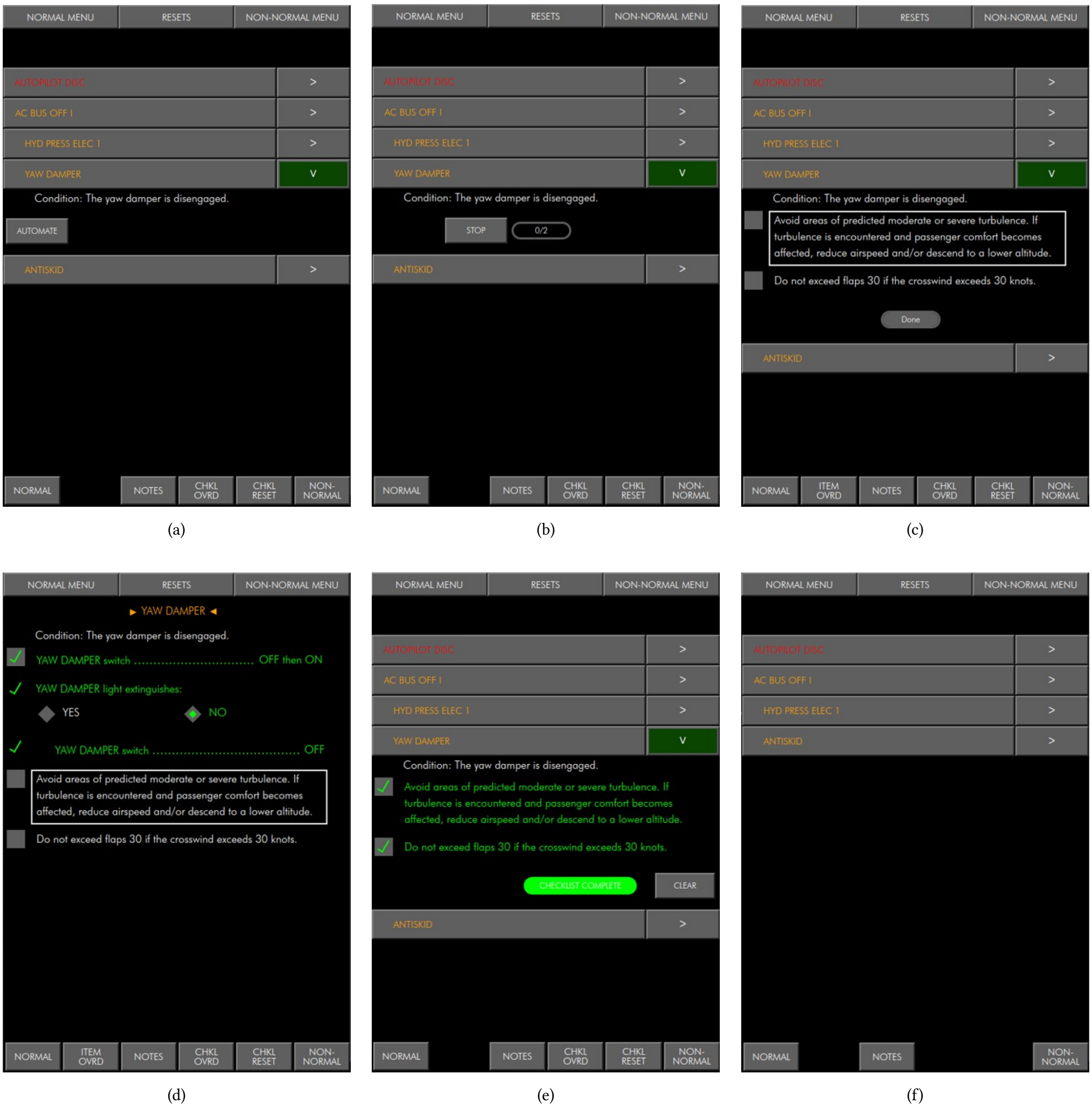


Figure 7.3: Checklist automation is started in **(a)**, in progress in **(b)**, and finished in **(c)**. Additionally, through conditional line items, the checklist content is dynamically updated in **(c)** with two more open loop line items. In **(d)**, the AECL is compared against the ECL at the current state of progress, from which it can be observed that three out of fives steps are automated and not in the dropdown menu. After the completing the remaining two open loop line items in **(e)**, the AECL displays a green bar stating 'Checklist Complete'. Finally, in **(f)**, the checklist is now 'cleared' from the non-normal menu

(a) (b)

Figure 7.4: The three zones of the automation and checklist handling bar. Zone left handles automation, zone middle allows the pilot to supervise automation **(a)** and checklist progress **(b)**, and zone right is responsible for removing checklists from the non-normal menu once completed

checklists are collapsed. Moreover, when a checklist is expanded, the buttons only appear when on the same non-normal menu page of the AECL. Otherwise, a checklist might be accidentally impacted when not in view.

7.6. The Difference with Automation

Using the yaw damper checklist as example, the difference between the Boeing 787 ECL and the automated ECL can be observed from Figure 7.5 and Figure 7.6. The automation completes the first three steps, with as result two open loop line items to be completed by the pilot. The number of steps shown in the dropdown menu and completed by the pilot dropped with 60% when compared against what a pilot has to perform on the Boeing 787 ECL.

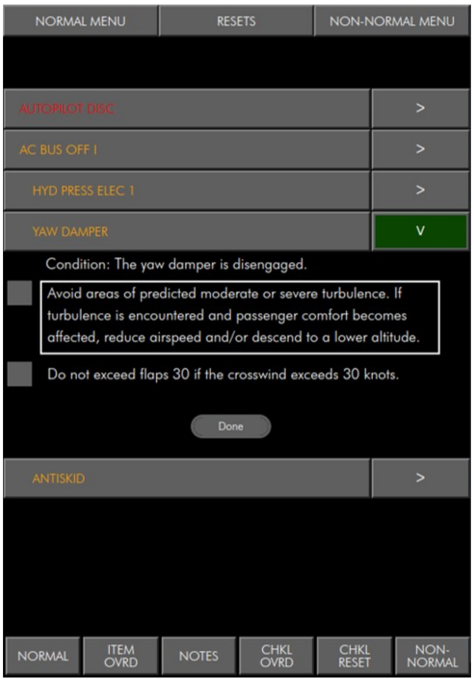


Figure 7.5: The step-by-step process as on the Boeing 787 ECL. Note that the first three steps would have been automatically complete with automation

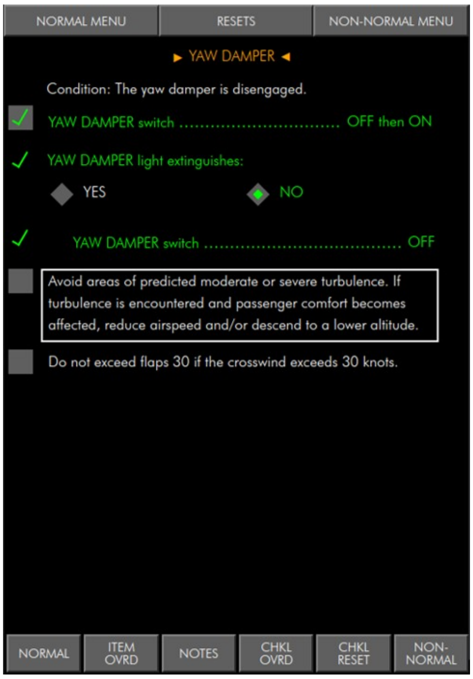


Figure 7.6: In the automated ECL, only the last two open loop line items are presented to the pilot, a reduction of 60%

IV

Appendix

A

The Experiment Design

This chapter will outline the experiment design of the human-in-the-loop experiment in which two scenarios were performed to compare the newly proposed AECL design against the reproduced state-of-the-art Boeing 787 ECL. First, the independent variables in section A.1 are outlined followed by section A.2 in which the apparatus is discussed. Thereafter, more detail follows on the dependent measures (section A.3) and the control variables (section A.4). Then, the programming, data analysis, and participant criteria are described in section A.5, section A.6, and section A.7, respectively. Finally, this chapter is complemented with the experiment hypothesis in section A.8.

A.1. Independent Variables

The experiment design has two dimensions of independent variables:

- Electronic checklist designs, and
- Scenarios.

A.1.1. Electronic Checklist Design

The ECL design as an independent variable is a consequence of the research objective; comparing the AECL against the current state-of-the-art ECL of the Boeing 787. The display configuration was a between-subject setup, as explained in subsection A.7.1. For more background on the designs, the current state-of-the-art ECL is discussed in chapter 2 and the novel proposed AECL is presented in chapter 6 and chapter 7.

A.1.2. Scenarios

In the experiment, participants were presented with two scenarios wherein a failure was introduced. Since every participant completed two scenarios, the independent variable is a within-subject independent variable. Throughout each scenario, participants were presented with a non-normal event, and their task was to assess the information, get the aircraft in the correct configuration, and propose a plan on how to resume the flight. Information on the non-normal event could be perceived through various indicators and displays and the checklists presented on the ECL/AECL. As discussed in chapter 2, checklists are vital to get the aircraft in the correct configuration. As such, every participant was tasked to complete all presented checklists. Meanwhile, the participant needed to construct a plan of approach for the continuing flight, e.g., is a deviation necessary or can the flight be resumed as planned. Note that the execution of such plan was not required, rather the participant focused on the analysis and the decision-making process where flying the aircraft itself was outside the scope of the experiment. Additionally, for both scenarios, a concurrent task was present (see subsection A.4.1 for a description).

Each scenario covered two different domains of the Boeing 737 systems, namely the hydraulics and the electrics. The hydraulic failure occurred due to a reservoir leak, whereas the electrical failure happened due to a drive shaft failure. Covering multiple domains generates more data points and spreads the risk of potential knowledge gaps between participants. One participant can, for example, be disproportionally knowledgeable about electrical failures and inflate performance for that specific group. With more domains, the participant's

Table A.1: Apparatus information

Display	Dimension	Aspect Ratio	Resolution	Touchscreen
ECL and Middle Panel	15”	4:3	XGA	Yes
Overhead Panel	42”	9:16	UHD	Yes
Primary Flight Display and Navigation Display	21.5”	16:9	UHD	Yes
Master Caution	15.6”	9:16	FHD	Yes
Aft Pedestal	19.5”	9:16	FHD	Yes
Mode Control Panel	N/A	N/A	N/A	No

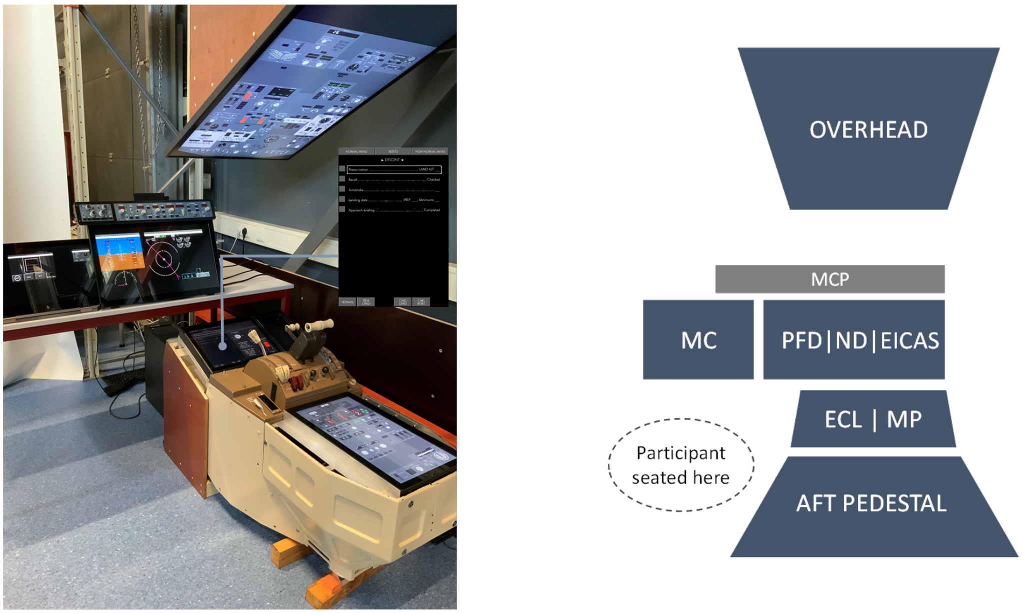


Figure A.1: The participant was seated on the left. The overhead panel was located above the participant, and in front of the participant, from left to right, was the Master Caution (MC) display, the Primary Flight Display (PFD), Navigation Display (ND) and EICAS. Above mentioned displays, the Mode Control Panel (MCP) was situated. On the right side of the participant, the ECL, the Middle Panel (MP) and the aft pedestal could be found. Note that the MP was a custom solution to facilitate switches and indicators which were impossible to integrate on their actual location. All displays in blue were operable by touch

knowledge is more generalised, although such risks remain to exist. Additional discrepancies between the scenarios included the number of checklists presented to the participant. A detailed review on the technicalities and systems is provided in section B.3 and section B.4 for the electrical and hydraulic failure, respectively.

A.2. Apparatus

The experiment was conducted in a stationary setup replicating the Boeing 737 cockpit from the of point of view of the left-positioned pilot, for this experiment the PNF. The apparatus setup is shown in Figure A.1. The ECL was positioned between the aft pedestal and the row of displays in front of the participant. The row contains, from left to right, the Master Caution (MC), the Primary Flight Display (PFD), Navigation Display (ND), and EICAS. As can be seen in Figure A.1, a combination of displays was shown on one screen (e.g., the ECL and the MP). The overhead was positioned above the pilot at the inclination as in the Boeing 737 cockpit. Finally, the Mode Control Panel (MCP) was placed on top of the two screens in front of the participant.
All screens, and the thereon presented panels and displays, were operable by touch. For example, this includes moving a switch on the overhead as well as turning off the master caution. The exception, however, was the MCP, which was still mechanical. Refer to Table A.1 for an overview of the screens used.

Table A.2: An high-level overview of the dependent measures split out in objective and subjective independent variables

Objective dependent measures	Subjective dependent measures
Performance	Experienced Workload
Choice of Airport	Situation Awareness
Decision Time	Acceptance
Concurrent Task	

A.3. Dependent Measures

Two types of dependent measures were used in the experiment: objective and subjective measures. The objective measure data - performance, choice of airport, decision time, and the concurrent task score - were directly measured during the experiment. The subjective data, however, was based on post-scenario subjective input by the participants and covers: experienced workload, situational awareness, and acceptance. A summary is presented in Table A.2.

A.3.1. Performance

The performance dependent measures aimed at measuring the speed by which checklist completion was performed, named the time to completion. Completion of all checklists indicates the aircraft is set into the correct configuration with respect to the experienced failure. Lower times to completion might indicate a lower workload for a task, frees up cognitive resources and time for other tasks, and shows the design's ability to get the aircraft in the correct configuration. However, it should be noted that time to completion can be affected when the pilot is intervened with a concurrent task while executing a checklist. Two variants of completion times were assessed, the time to set the aircraft in the correct configuration following the NNCs (gross) and the time to completion when only counting the time spent actually completing the checklists itself (net).
Accuracy was deliberately disregarded since both ECLs only allow a checklist to acquire a status of completion when all steps are completed correctly. Furthermore, at the participant's discretion, a step may sometimes be intentionally ignored by overriding the line item, resulting in an incomparable measure.

A.3.2. Situational Awareness

During the experiment, situation awareness was measured with the Situation Awareness Rating Technique (SART) test [109]. SART is a post-trial subjective rating technique and uses 10 dimensions to measure operator situation awareness: familiarity of the situation, focusing of attention, information quantity, information quality, instability of the situation, concentration of attention, complexity of the situation, variability of the situation, arousal, and spare mental capacity. Each dimension is rated on a scale from 1 (low) to 7 (high) based on the participant's subjective performance. The dimensions were subsequently combined to obtain the final SART score, and was calculated using Equation A.1, where U is the summed understanding, D is the summed demand, and S the summed supply.

$$SART = U - (D - S) \tag{A.1}$$

An overview of the domains and the corresponding dimensions and definitions are presented in Table A.3. SART is a widely applied measure, quick and easy to administer, and non-intrusive. Disadvantages of utilising SART, however, include post-hoc difficulties (e.g., no variability over time and too much weight on later stages of assessment) and the fact the participant is rating on a subjective basis.

A.3.3. Experienced Workload

To measure workload, the Rating Scale Mental Effort (RSME) was applied [110]. The RSME is a post-hoc measurement and thus non-intrusive. The workload was subjectively indicated by the participants on a scale from 0 to 150 with ticks per 10 units. To guide the participant, labels along the vertical axis were included which describes the experienced effort, as shown in Figure A.2. Note that the RSME is calibrated to the participant's preferred language, as can be seen in Figure A.2a for English and Figure A.2b for Dutch. The measurement technique is easy to use and quick for the participant and does not suffer from definition interpretation as can be experienced when using the NASA TLX. However, at the same time, it gives more detail than rating techniques such as the ISA. The downside is the subjectivity of the measurement and that the workload is

Table A.3: A breakdown of every dimension and corresponding definition of each domain of the SART test [109]

Domain	Dimension	Definition
Attentional Demand	Instability of the situation	Likeliness of situation to change suddenly
	Variability of the situation	Number of variables that require attention
	Complexity of the situation	Degree of complication of situation
Attentional supply	Arousal	Degree that one is ready for activity
	Spare mental capacity	Amount of mental ability available for new variables
	Concentration	Degree that one's thoughts are brought to bear on the situation
	Division of attention	Amount of division of attention in the situation
Understanding	Information quantity	Amount of knowledge received and understood
	Information quality	Degree of goodness of value of knowledge communicated
	Familiarity	Degree of acquaintance with situation experience

measured after the scenario. Therefore, no changes in workload during the experiment can be observed, and later instances can be weighed more heavily, affecting the RSME score.

A.3.4. Choice of Airport and Decision Time

The choice of airport is a proxy of the operator's decision-making quality, which can only be achieved after obtaining good situation awareness. The decision itself is complemented by participant commentary wherein their thoughts and rationale are outline. Refer to appendix M and appendix N for more detail.

The decision time describes the time required for the choice of airport. Low decision times might hint towards fast development of situation awareness and decision-making.

A.3.5. Concurrent Task Score

The score obtained for a concurrent task (see subsection A.4.1 for a description) shows the participant's ability to split its cognitive resources. A good score for the concurrent task is essential as it exemplifies concurrent real-life tasks such as ATC communication. A bad score can indicate that the participant is suffering from attentional tunneling or a too high workload. The concurrent task score was obtained by measuring the accuracy by which the participant completes the task.

A.3.6. Acceptance

The Crew Acceptance Rating Scale (CARS) [111] is a scalar measure that aims at measuring the operational acceptability of a new system or design to identify if the new design is deemed as effective and suitable by their operators. CARS is an adapted version from the Cooper-Harper test. The drawback is that CARS requires specific customisation for every experiment. The CARS used in the experiment is depicted in Figure A.3. A score of 10, the highest possible score, indicates complete satisfaction form the operator, whereas a score of 1 indicates drastic improvements are mandatory.

A.4. Control Variables

This section discusses the control variables of the experiment. Below, an overview is provided with the control variables and their primary considerations:

- Concurrent task: a parallel task which required participants to respond to ATC messages throughout each scenario to increase participant workload and add realism. Also, concurrent tasks are often a constraining factor during non-normal events [19] and situation awareness development [90].
- Checklists: the checklist content was presented as per the Boeing 737-8 QRH [34].
- Pilots: aircraft type rating, experience in flight hours, flight deck position, and current employer.
- Apparatus: the types, dimensions, and positioning of the screens used.

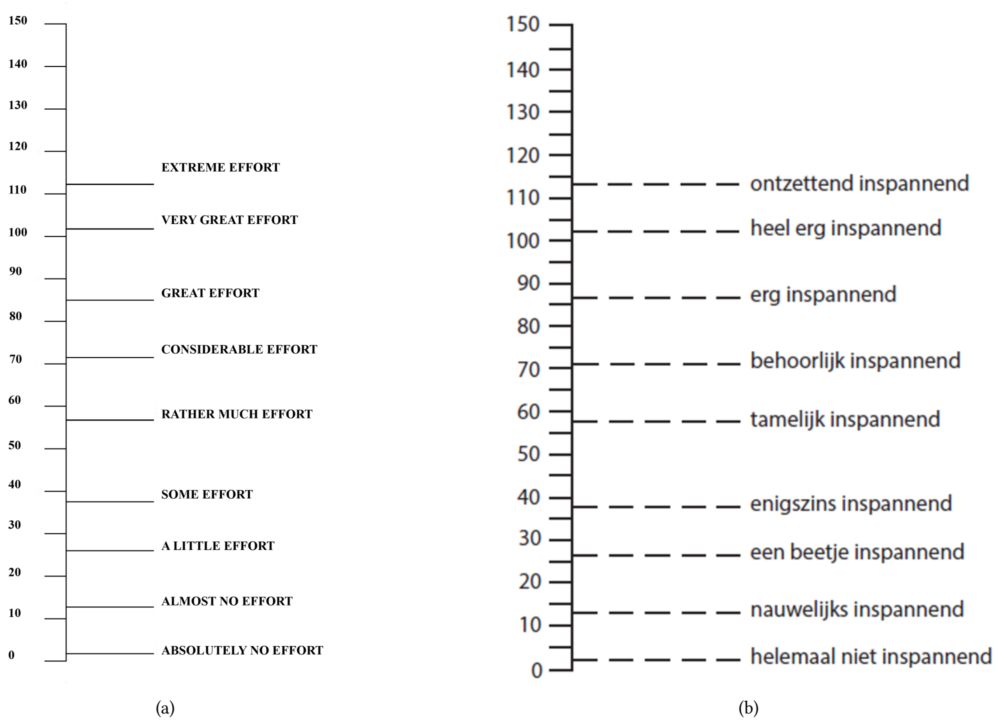


Figure A.2: Rating Scale Mentor Effort [110] for (a) English and (b) Dutch calibration

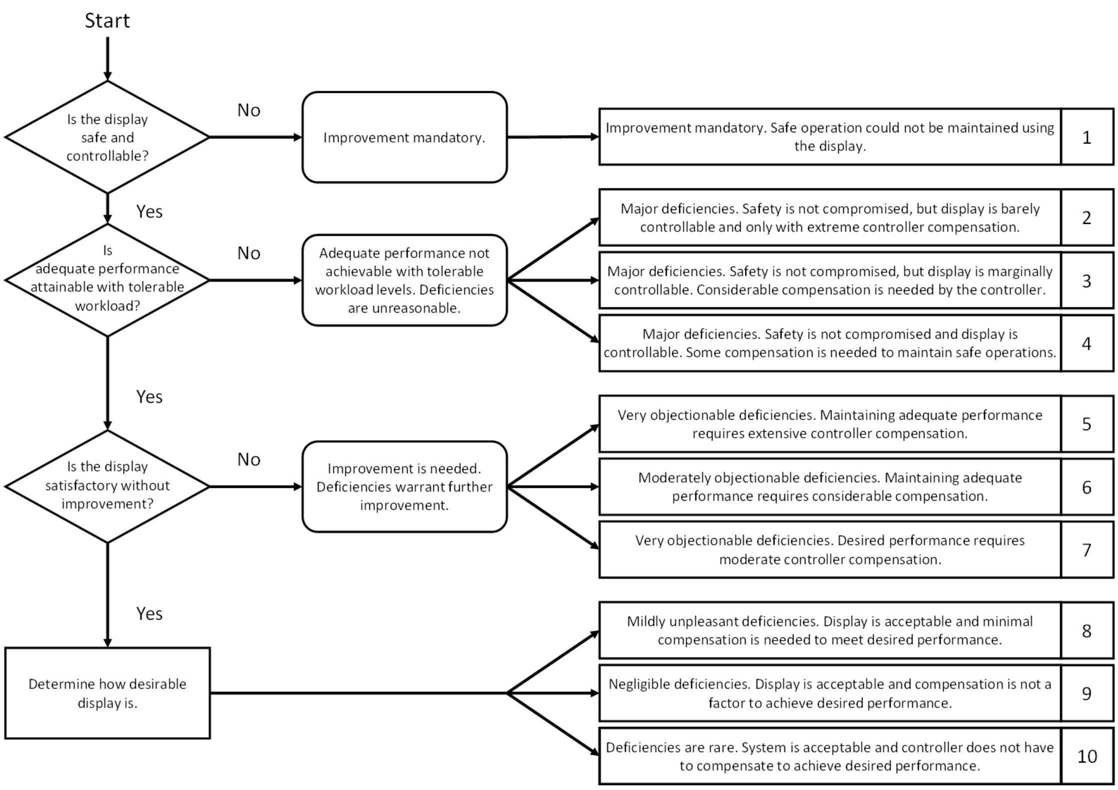


Figure A.3: Crew Acceptance Rating Scale

- Training: the amount and thoroughness of training the participants received before starting the experiment.
- Flight plan: what information was presented before starting the scenarios and how this was communicated to the pilot.
- Automation speed: the assumed time required by automation to move a switch to a certain position. For the experiment, this value was set at 0.5 seconds to guarantee a switch is in its correct position and give the flight deck ample time to recognise the new configuration before advancing.

A.4.1. Concurrent Task

For the concurrent task, pilots over set intervals received 5 ATC messages from which one corresponded to the participant's aircraft callsign (DUT[1] 961, prounced Delta Uniform Tango Niner Six One). The order and content of these messages were randomised and rotated to avoid learning. A preprogrammed voiceover asked the participant to report back a certain aircraft state or an element of the flight plan (e.g., flight speed, altitude, and the airport of destination). The concurrent task was introduced to enhance the reality of the experiment, wherein real-life ATC communication and other competing tasks are present, and to enforce stress and workload to better test events on the more extreme side of the spectrum. Furthermore, attending the concurrent task requires attention switching, which stresses the display's operational flexibility, since attention switching can result in inaccuracies and increased time to completion of the checklist. The concurrent task was evaluated on the accuracy of the response, which is the ultimate conclusion of a set of questions: does the participant respond? Is the response to the correct callsign? And does the participant answer correctly?

A.4.2. Pilots

First of all, the technical knowledge required to resolve the presented failures required the participants to be a professional pilot type-rated on the Boeing 737.

Pilots build experience over time to improve system and aircraft knowledge. Moreover, as discussed in section 5.2, increased experience builds a better relationship between working memory and long-term memory, making one's cognitive abilities more efficient. Therefore, it is preferable if there is comparable experience among the participants. Additionally, the pilot's position on the flight deck (Captain or First Officer) may influence results since a Captain is more experienced and trained to drive the decision-making process, with the First Officer in a supporting role.

Another component of the pilot control variable is the current employer of the participant. This is relevant since different airlines may have different operating procedures and different equipment on board. Although the flight plan and the flight deck during the experiment were generalised, factors driving the decision-making can be airline specific. Therefore, a careful note was taken about any discrepancies between participants' employers.

A.4.3. Training

A dedicated training scenario with made-up checklists was performed multiple times to make sure the participant was fluent in navigating the display and the touch flight deck before beginning the measurement stage. To emphasise on this, a hypothetical non-normal scenario was constructed. Herein, no logical system knowledge was required, rather the focus was on the participant becoming affluent with any type of action required during the experiment. This would include, the various step types from Table 6.1, a disconnecting autopilot, and the various functions of the ECL/AECL display. During the briefing, specific instructions were communicated that, for the AECL, checklist completion was only to be performed through automation, in order to guarantee the design was used as intended. Nonetheless, it was allowed to access the checklist before and after the completion process to give opportunity to develop context where needed.

A.4.4. Procedure

The experiment started with a technical briefing, discussing the flight deck, EICAS, the relevant ECL display (ECL or AECL), the flight plan, and the tasks at hand (primary and secondary). Subsequently, the training phase set off which was repeated until both the participant and experimenter were completely comfortable with the participant's fluency in operating the display and flight deck in order to avoid mistakes attributable to display and flight deck unfamiliarity.

[1] Delft University of Technology

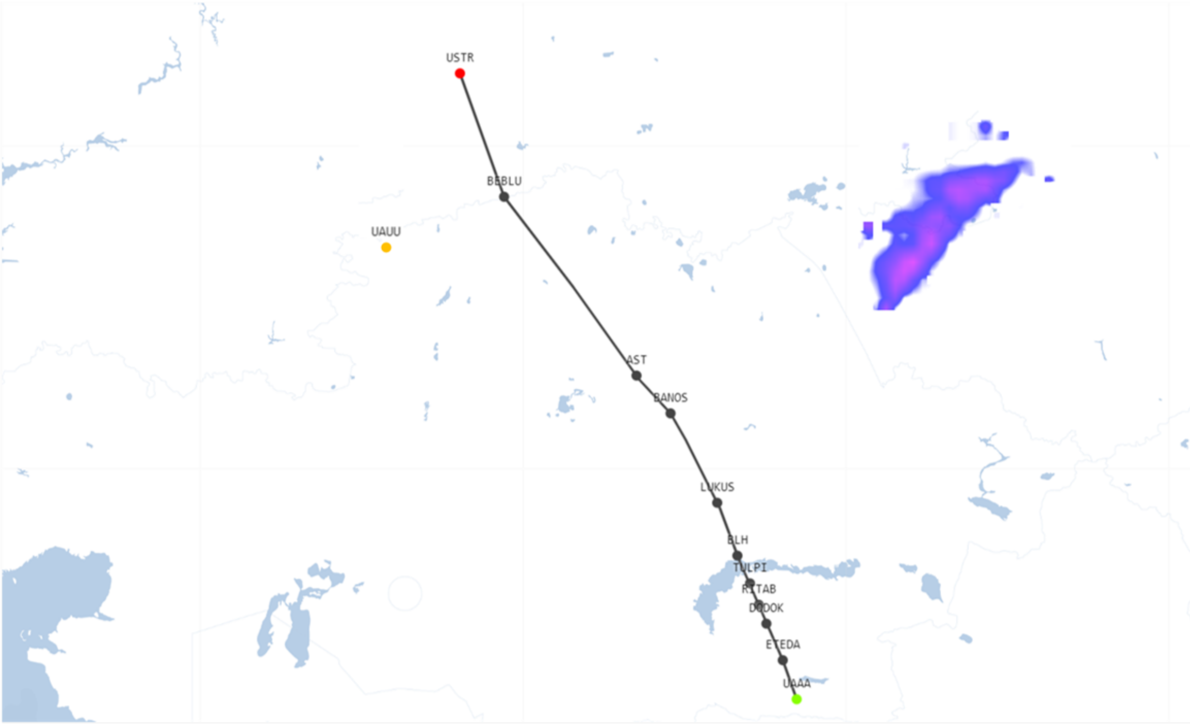


Figure A.4: Map of the flight plan. Departure airport was UAAA (green dot), destination was USTR (red dot), and destination alternate was UAUU (yellow dot). All scenarios started from checkpoint AST

After the briefing and training, two measurement scenarios were completed: the drive shaft failure and the hydraulic leak failure, each succeeded by participants indicating their experienced workload, situation awareness, and commentary on their decision rationale and thoughts on the nature of the failure.
A short debrief was administered when both scenarios were completed, which asked participants to indicate an acceptance score and to provide feedback on the design and touch flight deck. In total, the experiment duration averaged around 3-3.5 hours per participant.

A.4.5. Flight Plan

To simulate realism and to provide context to the scenarios, the flight plan was an instrumental part of the experiment. The flight plan (see I) content included information about the departure, planned destination, and destination alternate airport. Airport information comprised information about the weather, the runways, available approaches, and the location. Moreover, the planned route was presented through both coordinates and a map (see Figure A.4), which participants could refer back to on the ND during the experiment. The flight commenced from Almaty, Kazakhstan (UAAA), the planned destination is Roshchino, Russia (USTR), and the destination alternate is Kostanay, Kazakhstan (UAUU). Both scenarios started from waypoint Astana, Kazakhstan (AST). All airport and route waypoints exist in real life and the information in the flight plan was taken from actual data. However, the weather (METAR and TAF), runways, and NAVAIDs were altered to fit specific needs of the experiment and to avoid any potential prior knowledge bias of the participants (for example, KLM used to fly on Almaty). Finally, aircraft specific information about various weights (e.g. take-off weight and fuel weight) and the aircraft callsign were shared through the flight plan (see appendix I).

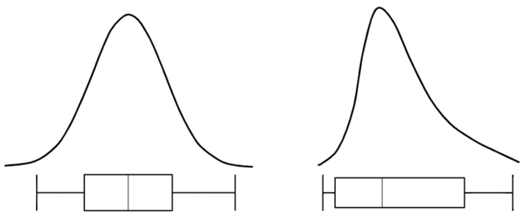
The flight plan was also a tool to test situation awareness by including elements to drive the decision-making by design. Depending on the scenario (as explained in appendix B), a specific airport should have been chosen for landing. For both scenarios the pilots had the option to divert to the alternate airport, or to continue as planned. From the map it can be noted that UAUU (destination alternate) is closer than USTR (destination). Another significant difference was that destination alternate only has one RNAV approach available, whereas the destination provided three ILS approaches. Furthermore, factors such as weather, wind, and others were set relatively equal and should not have (and did not) influenced the decisions made.

A.4.6. Checklists

Although the scenarios itself were independent variables, the associated checklist content was considered a control variable. The material presented were identical for every participant and was sourced from the Boeing 737-8 QRH [35]. Though, slight alterations in the content were made to facilitate the transfer to an electronic version on the ECL. Such alterations included the specification of the system. For example, the QRH would present the checklist: Source Off. The ECL/AECL, however, specified which side the checklist referred to: Source Off 1 or Source Off 2. For more details on which checklists are included in the scenarios, see appendix B, appendix C, and appendix D.

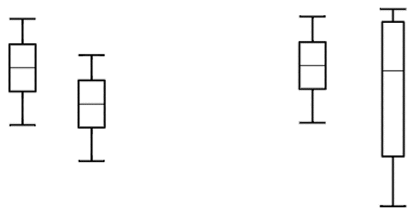
A.5. Programming

All displays and panels (see Figure A.1) were programmed through a combination of JavaScript, HTML, and CSS. JavaScript was responsible for the display logic and simulation, whereas the HTML and CSS code was controlling the display layout. All data utilised by the mentioned code is provided in JSON format converted from various Excel input sheets. The digital flightdeck was accessible and configurable through a browser from which also the scenarios can be started. JavaScript was also responsible for collecting all data during the measurements and writing this to a CSV file. The ultimate data analysis and presentation, however, was performed with Python. Appendix E depicts an high-level schematic overview of how the software was organised.



(a) (b)

Figure A.5: (a) shows an example of a normally distributed sample data set with its corresponding boxplot, and (b) indicates a (left) skewed data set with a corresponding boxplot that does not satisfy the normality assumption [112]



(a) (b)

Figure A.6: (a) depicts boxplots satisfying the sphericity assumptions, whereas (b) does not satisfy this assumption [112]

A.6. Data Analysis

After obtaining the experimental results, the data was analysed by employing a statistical study. This section elaborates on the statistical analysis performed. The data analysed were the time to completion, situation awareness, experienced workload, choice of airport, decision time, concurrent task score, and acceptance. In section A.3, a comprehensive overview is provided on all dependent measures of the experimental test.

All analysed data were evaluated for their statistical significance to assess if any found relationship is by chance or some factor of interest. In this research, the null hypothesis was rejected – there is statistically significant evidence – when the obtained p-value is less than 5%. It describes the conditional probability that, when assuming the null hypothesis is true, the observed results are at least as extreme as found from the sample data.

Before selecting an appropriate test, the underlying distribution of the sample data was analysed to choose a parametric or non-parametric test domain. Parametric tests are preferred since they are more efficient and they are usually more powerful [112]. However, for using a parametric test, two assumptions should hold; the assumption of normality and the assumption of homogeneity of variance. For each experiment condition the following procedures are applied:

- **Testing for normality**: the data was visually inspected through a Q-Q plot and a boxplot (see Figure A.5). Subsequently, the conclusion was validated when using the Shapiro-Wilk test.
- **Testing for homogeneity of variance (sphericity)**: the data was visually inspected through box plots (see Figure A.6). Subsequently, the conclusion was validated using Levene's test (for a between-subject design) [112].

For every dependent measure, considering the experiment follows a between-subject design (subsection A.7.1) and contains two independent variables (see section A.1), a One Way Independent ANOVA was to be used when both the parametric assumptions hold. When either of the assumptions is violated, the Mann-Whitney U test was to be used as a non-parametric statistical test. Following the results and the relatively limited number of data points, six per design, the Mann-Whitney U test was used for all dependent measures.

A.7. Participants

In total, 14 participants volunteered to partake in the experiment. Due to the specific system knowledge requirements of the experiment, the participants are or were all recently active professional airline pilots on the Boeing 737, of which a brief profile is presented in Table A.4. Due to a steep learning curve involved for learning a new display and annunciation process and to avoid scenario recognisability, the experiment used a between-subject design. Thereby, every participant was assigned a single display with which two scenarios were conducted. The order in which the two scenarios were presented was equally distributed within both groups (see subsection A.7.2). Furthermore, two participants were type-rated on the Boeing 787 and therefore already had experience with EICAS and the ECL. They were equally divided over the two groups as well.

Table A.4: Participant background information (only includes participants for which the data was used in the analysis)

	Age	Total commercial flight hours	Boeing 737 flight hours	Profile
ECL				
Max	61	21,000	9,000	4 Captains and
Min	28	2,900	100	2 First Officers
Average	44	10,150	4,392	
AECL				
Max	50	12,000	11,500	2 Captains and
Min	27	3,500	2,000	4 First Officers
Average	35	6,800	4,600	

A.7.1. Motivation for the Number of Pilots

Due to the specificity of the scenarios, participants were most likely to recognise its characteristics when repeating the same scenario, and thus the data would suffer from learning effects. Moreover, since all participants required extensive training for each display, there was a risk of negative transfer and fatigue. Consequently, the experiment utilised a between-subjects design. As mentioned in section A.1, the experiment had two independent variables which each containing two levels: two ECL designs and two scenarios. Therefore, the total number of participants required was to be a multiple of 2. This multiple is subsequently multiplied with the number of data points per design. To obtain representative data, the total number of samples is set at six. Although utilising a higher number of pilots is beneficial to satisfy the parametric test assumptions, for practicality purposes, the number of samples was limited to six considering the use of Boeing 737 type-rated pilots. Moreover, since the pilots were all professionals and experienced, their performances were expected to be more closely aligned, allowing for lesser samples. As such, the total number of data points equals 12. As mentioned above, potentially faulty data points were expected, and to mitigate this risk, a total of 14 participants were invited.

A.7.2. Experiment Matrix

The experiment matrix was designed in the form of a Latin Square. This setup mitigates nuisance effects such as fatigue and effects of learning and is also an efficient way of scenario distribution. In the Latin Square, presented in Figure A.7, one can notice the shuffling of the conditions per participant over the two displays.

A.8. Hypothesis

Following the literature review (see Part II) and the design overview (see Part III), and the experimental setup of this chapter, the following hypothesis were drafted. It was hypothesised that for the AECL, when compared against the base case ECL:

- Experienced workload decreases as a result of automation.
- Time to completion decreases. With automation, less time is required to get the aircraft in the correct configuration. Moreover, since less attention shifting is required when omitting the manual work, participants can better focus on solving the non-normal event.
- Situation awareness is expected to remain unchanged. The automated design might suffer from out-of-the-loop complications [108] in terms of perception since part of the aircraft non-normal configuration is no longer done manually. However, such effects are expected to be minimal and not influence results. On the other hand, situation awareness may increase because of the freed cognitive resources due to the automation, which would allow for better comprehension and projection of future status. Again such effects are expected marginal since every participant during the experiment is not constrained in time.
- The concurrent task score is expected higher due to a product of lower expected experienced workload (and thus an enhanced capability to manage other tasks) and less attentional tunnelling when not manually completing steps.

Participant	Display	Scenario 1	Scenario 2
1	ECL	Drive Shaft Failure	Hydraulic Leak Failure
2		Hydraulic Leak Failure	Drive Shaft Failure
3		Drive Shaft Failure	Hydraulic Leak Failure
4		Hydraulic Leak Failure	Drive Shaft Failure
5		Drive Shaft Failure	Hydraulic Leak Failure
6		Drive Shaft Failure	Hydraulic Leak Failure
7	AECL	Drive Shaft Failure	Hydraulic Leak Failure
8		Hydraulic Leak Failure	Drive Shaft Failure
9		Drive Shaft Failure	Hydraulic Leak Failure
10		Hydraulic Leak Failure	Drive Shaft Failure
11		Drive Shaft Failure	Hydraulic Leak Failure
12		Hydraulic Leak Failure	Drive Shaft Failure

Figure A.7: Latin Square matrix with six participants per design (ECL and AECL). Each participant performs two scenarios (drive shaft failure and hydraulic leak failure), with the order of the scenarios equally distributed across both displays

B
Boeing 737 Systems

Following the Introduction, this research assumed the Boeing 737 as the underlying aircraft to base the operations and systems on for the experiment. As such, this chapter aims to elaborate on all the relevant systems with which pilots actively interacted during the experiment. First, in section B.1, the task at hand for both scenarios is addressed. After that, section B.2 continues with an overview of the Boeing 737 annunciation systems. This is followed by a detailed review of both failures, the drive shaft failure and the hydraulic leak failure in section B.3 and section B.4 respectively.

B.1. General Mission

For each design, a participant completed two scenarios in which a failure occurred during the flight, an electrical and a hydraulic failure. Both scenarios assumed the same flight plan and the failure occurred approximately at the same instance, a few minutes after passing waypoint AST, from which the simulation commenced. The participants were tasked to resolve the abnormal situation when such an event would arise. Accordingly, this would require to get the aircraft in the correct configuration, and as such, all incurred checklists are to be completed. Meanwhile, the participant needed to construct a plan of approach on how to continue the flight within the context of the flight plan, wherein factors such as operational feasibility and safety were to be considered. For example, one may opt to divert to UAUU, to continue as planned to USTR, or go back to the departure airport. Together, this tests checklist handling and the decision-making process.

Participants assumed the PNF role and could ignore any substantial tasks generally assigned to the PF, and were thus not concerned with flying the aircraft. Finally, autopilot A was the engaged autopilot and the APU was inoperative.

B.2. Annunciations

System malfunction detection on the Boeing 737 is a multistep process, often started through an illumination (and possible aural signal) of the master caution lights to grab the pilot's attention as it is conveniently located within the pilot's sight (on both sides of the cockpit), as can be seen in Figure B.1. Besides, the System Annunciator Panel (SAP) identifies the domain(s) of the failure (e.g., hydraulic domain (HYD), see Figure B.2) which the pilot can use as a starting point for assessing the issue. Often the pilot is referred to the overhead panel (see Figure B.6), where further illuminations guide the pilot. Master caution and SAP together form the fire warning and master caution system displayed in Figure B.2. Based on the illuminations and signals on the overhead and other panels and displays, the pilot employs the QRH and selects the checklist(s) appropriate for the indications communicated to the pilot.

This process, however, is different during the experiment, where the flight deck setup adopted the annunciation process of the Boeing 787 through a combination of the master caution system, EICAS, and the ECL. After the master caution system indicates an issue, the pilot can refer to EICAS, which annunciates all relevant messages, and if applicable, is connected to the ECL, which shows the associated checklist(s). This setup assumed a more digital flight deck and foregoes the manual process of identifying and finding the correct checklist(s). Hence, SAP was omitted and the fire warning and master caution system (Boeing 737 version) was replaced

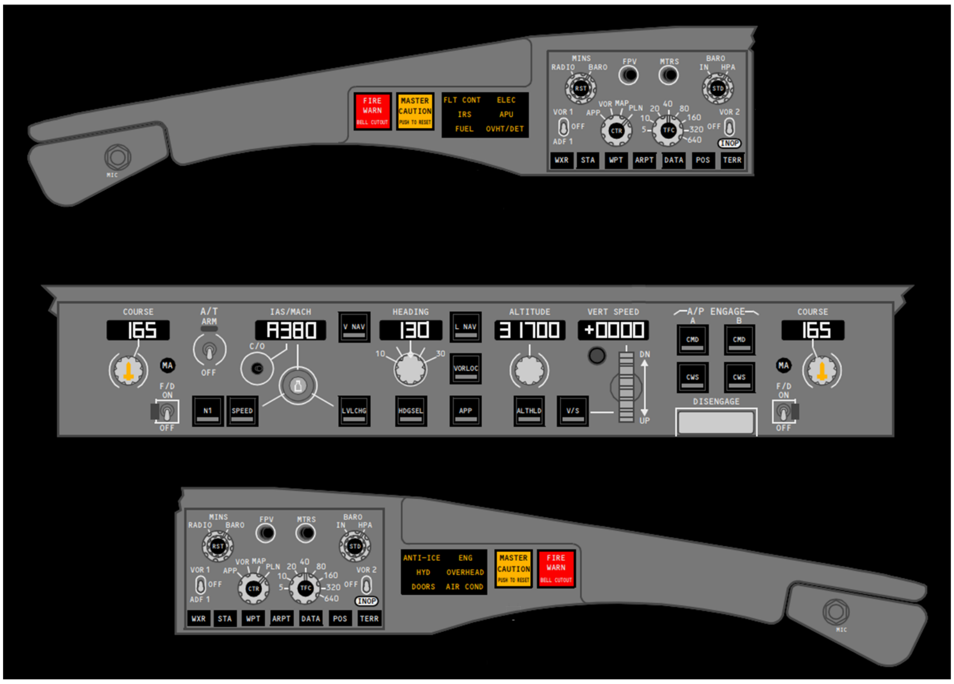


Figure B.1: The master caution system is located on both sides of glareshield panel. As a reference, the glareshield panel location within the flight deck can be seen in Figure B.4 [35]

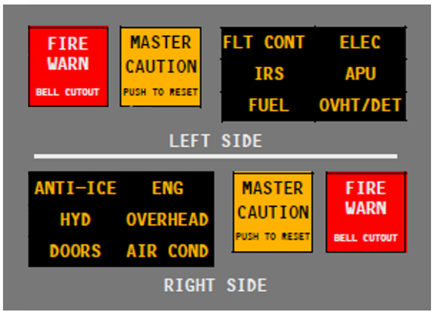


Figure B.2: Fire warning and master caution system of the Boeing 737 [35]

Figure B.3: Master caution system of the Boeing 787 [8]

with the master caution system (Boeing 787 version, see Figure B.3). Note that all other illuminations such as on the overhead panel still occurred, alike on the Boeing 787.

The Boeing 787 master caution system, illustrated in Figure B.3, contains two components; the red light indicating a warning and the amber light indicating a caution. A warning can correspond to a new EICAS warning message, or an engine fail, pull up, or windshear alert. For example, an autopilot disconnect triggers the warning light to illuminate, and EICAS will show a message indicating the autopilot disconnected. In addition, the master warning assumes the function of cancelling any aural alert when pushed (e.g., the autopilot disconnect horn). Master caution, on the other hand, becomes illuminated when a new EICAS caution message is displayed.

B.3. Scenario I: Drive Shaft Failure

The first scenario encompasses an electrical failure which through a dual malfunction and an inoperative APU caused numerous dependent systems to become inoperative. The failure is characterised by disarranged communication to the participant, who receives a wide array of checklists, 12 in total, which at first sight are not necessarily directly related. The high number of checklists challenges the participant to integrate and keep track of many sources of information and to build an understanding of the failure at hand. Both are vital to

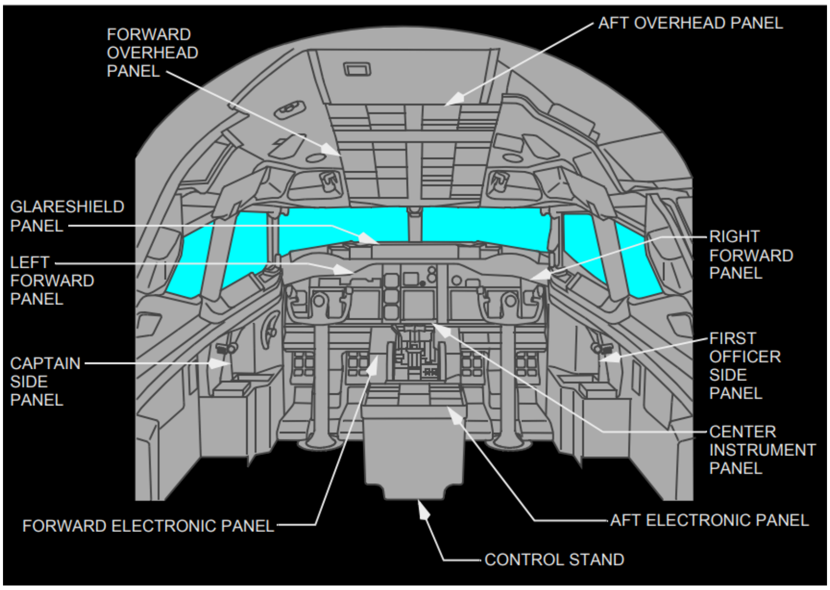


Figure B.4: The Boeing 737 cockpit with all its major panels and stands [35]

devise the course of the remainder of the flight.
This section will begin with an overview of the Boeing 737 electrical systems in subsection B.3.1, followed by subsection B.3.2, which describes the design of the failure. Finally, in subsection B.3.3, the consequences of the failure on the aircraft and the implications on the flight plan are outlined.

B.3.1. The Electrical System

The electrical system on the Boeing 737 has two principles: there is no paralleling of the AC sources of power, and the source of power being connected to a transfer bus automatically disconnects the existing source [35].
The electrical system has three main divisions: the AC power system, the DC power system, and the standby power system. Two engine IDGs provide primary electrical power and supply three-phase 115 volt, 400 cycle AC. Each of the IDGs supplies power to its respective AC transfer bus through a generator circuit breaker during normal operations. In case of a failing IDG, the BTB system will allow both AC transfer busses to be supplied by the remaining IDG, which can be achieved by closing both BTB 1 and BTB 2. Additionally, when available, the APU operates a generator and can supply power to both AC transfer busses. The TR units and the main battery supply DC power.
TR 1 and TR 2 are supplied with AC power from their AC transfer bus 1 and AC transfer bus 2, respectively. Additionally, a third TR is responsible as backup and as a primary power source for the battery bus. The DC system consists of three busses: DC bus 1, DC bus 2, and the battery bus. The main and auxiliary batteries also supply backup power to both the standby AC and standby DC systems. A schematic overview of the electrical system is presented in B.5.

B.3.2. The Failure

The scenario was modelled as a failing drive shaft on the left-hand side. This caused the DRIVE 1 light on the overhead panel to illuminate and EICAS to display the corresponding message. Since no APU was available to compensate, and to keep both AC transfer busses supplied, the system will close the BTBs to connect the right IDG to both transfer busses. However, the BTBs for this scenario were not functioning as expected and AC transfer bus 1 did not receive the required electrical power, causing AC transfer bus 1 to stop working. This resulted in the illumination of the SOURCE OFF and TRANSFER BUS OFF lights on the left side and two more messages on EICAS. Also, the A-side autopilot (which was engaged) was now disconnected and the autopilot disconnect horn sounded. Autopilot B, however, was still available and could be connected. By now, both the warning and caution lights illuminated on the master caution system. AC transfer bus 1 is solely responsible for powering various subsystems, which shortly failed after the loss of AC transfer bus 1. Subsequent annunciations on the overhead panel and EICAS were the YAW DAMPER, LOW PRESSURE lights for fuel pump 1 FWD, fuel pump 2 AFT, and hydraulic pump ELEC 1, TEMP PROBE, L ALPHA VANE, and L ELEV PITOT heat lights, and

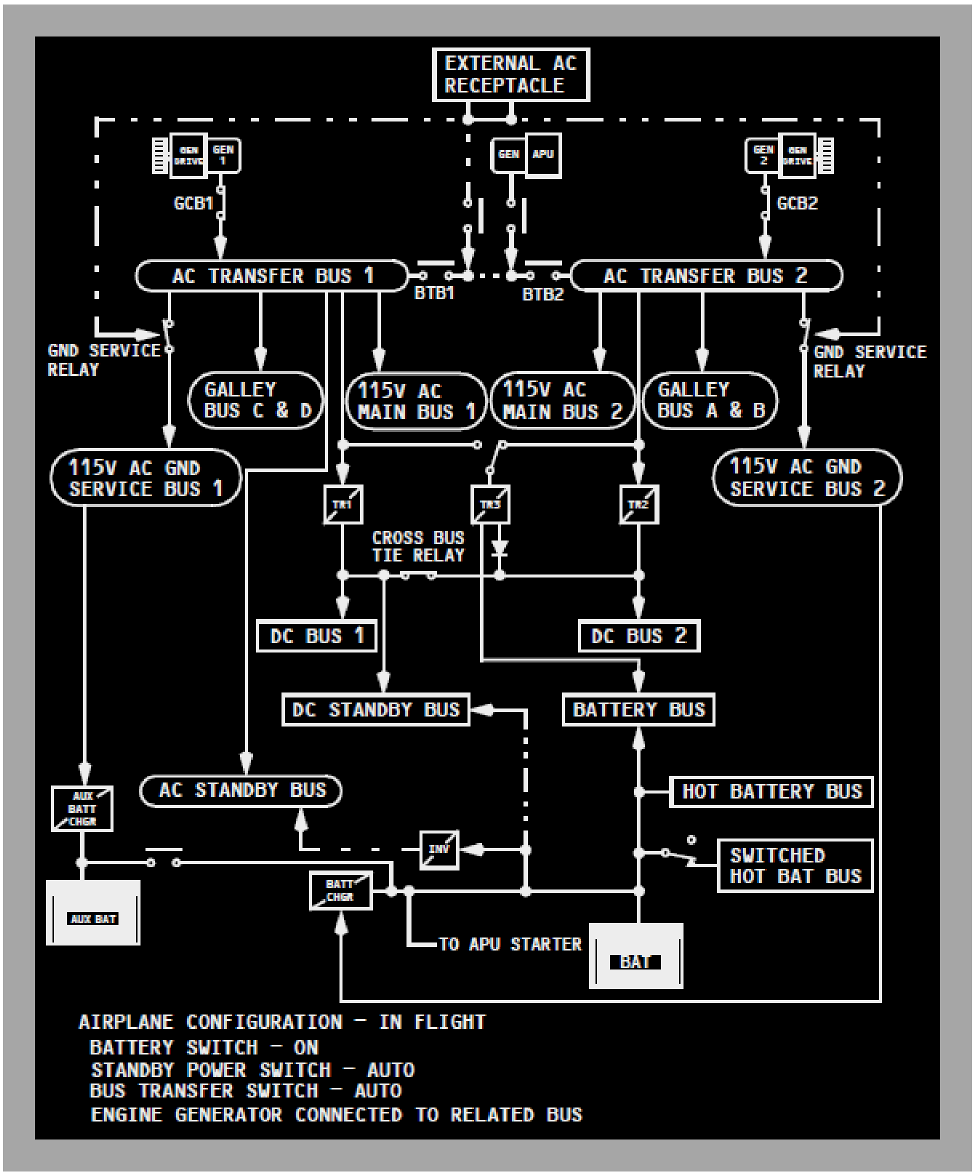
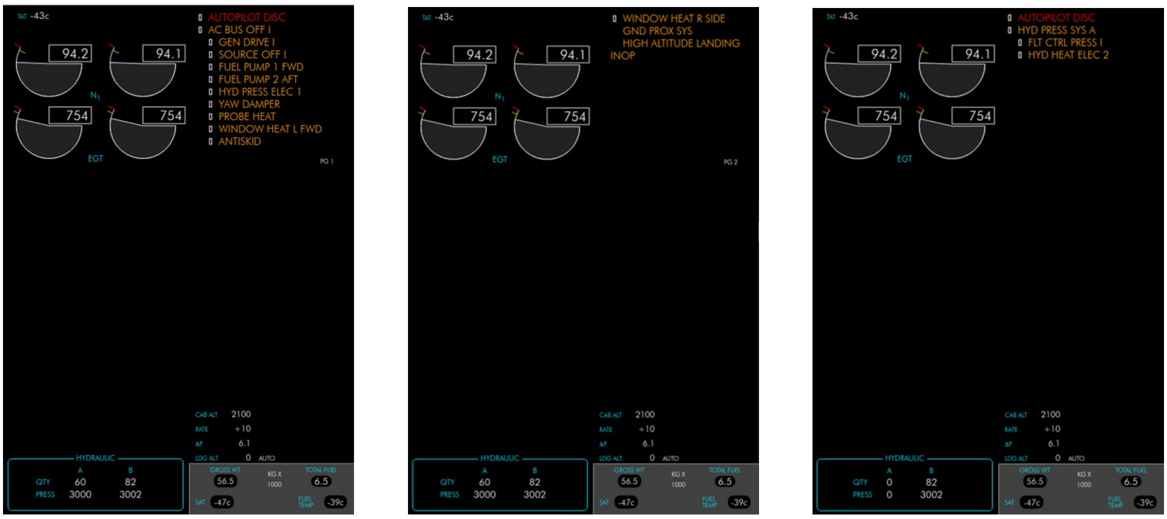


Figure B.5: Schematic overview of the Boeing 737-8 electrical system [35]

Figure B.6: The overhead panel for the Boeing 737-8. Indicated in blue are the lights illuminated during the drive shaft failure, whereas the indications are in orange for the hydraulic leak failure



(a) Drive shaft failure (1/2)

(b) Drive shaft failure (2/2)

(c) Hydraulic leak failure

Figure B.7: Overview of EICAS messages presented to the participant for the drive shaft failure in **(a)** (messages page 1) and **(b)** (messages page 2) and the hydraulic leak failure in **(c)**

window OVERHEAT lights for L FWD and R SIDE. Each of which providing the associated checklist on the ECL. Additionally, ANTISKID, with an associated checklist on the ECL, is reported on EICAS as well as GPWS INOP and HIGH ALT LAND INOP which also were annunciated through the INOP light on the aft pedestal. All annunciations and checklists appeared within approximately 4 seconds after the first illumination (which was the DRIVE 1 light). In Figure B.7a and Figure B.7b, the EICAS messages as presented during the experiment are shown, whereas Figure B.6 indicates the experienced illuminations on the overhead panel for the drive shaft failure. Finally, in appendix C, all checklists incurred are presented including a walk-through.

B.3.3. What Systems Are Lost and How to Continue the Flight?

Loss of autopilot A results in no autopilot redundancy, prohibiting any set of actions where this is required, such as a CAT III approach and some cases CAT II approaches[1]. Losing the yaw damper puts restrictions under which crosswinds the aircraft can safely land. Another weather-induced restriction comes from the probe heat becoming inoperative. The probe heat is no longer capable of heating instrument probes, and thus it is advised to avoid icing conditions. Also, the need for longer landing distances should be taken into account with the antiskid becoming inoperative, causing an inoperative autobrake system and the unavailability of locked wheel protection.

AC transfer bus 1 is responsible for powering the Radio Altimeter (RA) on the left side, which is now no longer operational. Although the aircraft has an RA on both sides, no redundancy is in place. This also causes the dependent GPWS to be inoperative. The GPWS is responsible for alerting the aircrew of immediate danger of flying into obstacles or terrain. Additionally, special attention should be paid to the loss of the TCAS. As an ultimate result, the outcome of multiple checklists is the advice of landing at the nearest suitable airport.

The participant is thus tasked to find the nearest airport that is suitable with respect to the new aircraft conditions. The airport information, such as the weather, runways, altitude, distance, and the approach NAVAIDs can be sourced from the flight plan (see appendix I). First of all, the departure airport is too far away to be considered. Therefore, the participant is left with the choice between the planned destination and destination alternate. Between the two, destination alternate is closer; however, it should be assessed whether destination alternate is the most suitable. Destination alternate has two approaches, ILS and RNAV, of which the ILS approach is out of service at the time of flight (see subsection A.4.5, appendix A, and appendix I), effectively leaving the RNAV approach as the remaining option. Notwithstanding the closer proximity of destination alternate, according to other literature RNAV approaches are no longer authorised with the loss of AC transfer bus 1 and and inoperative APU [15]. However, as follows from the discussion in Part I of this report, not for

[1]Depending on local decision heights

all participant's employers this restriction holds. For the airlines that no longer authorise RNAV approaches with this failure, the requirement for a dual RA is the restricting factor. The destination airport by design has multiple ILS approaches which were still allowed. Apart from the discrepancies in approaches between the two destinations, no other considerable differences were present. As such, both options are possible. The added distance of the planned destination is not substantially greater and would be commercially and operationally more attractive. On the other hand, in some cases, the specific checklist instruction of landing at the nearest airport would be ignored when not diverting to destination alternate.

B.4. Scenario II: Drive Shaft Failure

This section discusses the planned hydraulic leak failure. First, in subsection B.4.1, the hydraulic system is touched upon, followed by an outline of the failure design in subsection B.4.2. Finally, this section concludes with a review on how to continue the flight in subsection B.4.3.

B.4.1. The Hydraulic System

The Boeing 737 has three hydraulic systems: system A, system B, and the standby system. Both system A and system B are pressurised by bleed air and operate independently. They can separately power all flight controls with no decrease in aeroplane controllability [35]. All three systems have a reservoir, pumps, and filters, which pressure the reservoirs at 3,000 psi under normal conditions. Together, the hydraulic systems power: flight controls, leading-edge flaps and slats, trailing-edge flaps, landing gear, wheel brakes, nose wheel steering, thrust reverses, and autopilots.

More specifically, hydraulic system A is responsible for powering the following: ailerons, rudder, elevator, flight spoilers (two on each wing), ground spoilers, alternate brakes, engine 1 thrust reverser, autopilot A, normal nose wheel steering, landing gear, and the power transfer unit. Hydraulic system B on the other hand is responsible for powering the following components: ailerons, rudder, elevator, flight spoilers (two on each wing), leading-edge flaps and slats, normal brakes, engine 2 thrust reverser, autopilot B, alternate gear retraction, alternate nose wheel steering, and the yaw damper. The standby system powers the thrust reversers, rudder, leading-edge flaps and slats (full extend only), and the standby yaw damper. A schematic overview of the Boeing 737-8 hydraulic system is shown in Figure B.8.

B.4.2. The Failure

The hydraulic leak was assumed to be relatively large, causing a loss of 10 gallons per minute in reservoir A. Once the reservoir quantity dropped below 18.7% of a full tank, the LOW PRESSURE lights of ENG 1 and ELEC 2 of system A on the overhead panel illuminated. After approximately 30 seconds, the system A flight controls were annunciated on the overhead, and the corresponding message was displayed on EICAS. Also, the FEEL DIFF PRESS light illuminated as a result of the hydraulic system A pressure dropping more than 25% relative to hydraulic system B. Autopilot A, the engaged autopilot, was disconnected and the horn sounded, however, Autopilot B was available and could be engaged. The master caution system illuminated both warning and caution. In case the hydraulic system was not shut down within approximately one minute, the electric hydraulic pump OVERHEAT light illuminated with the associated message shown on EICAS. An overview of the EICAS messages and the overhead panel illuminations are shown in Figure B.7c and Figure B.6, respectively. Finally, in appendix D, all checklists incurred are presented including a walk-through.

B.4.3. What Systems Are Lost and How to Continue the Flight?

As mentioned in subsection B.4.2, the hydraulic system A is directly responsible for a set of the aircraft functions which now become inoperative. Despite losing hydraulic system A, two hydraulic systems were still available (system B and stand-by) which provide ample redundancy. This, in combination with sufficient fuel available and that standalone hydraulic system B can power the aircraft flight controls without suffering controllability losses, did not require the participant to land at the nearest suitable airport, as was instructed by the checklists in the drive shaft failure. Nonetheless, the impact on the aircraft should be assessed to determine if the destination airport was still suitable.

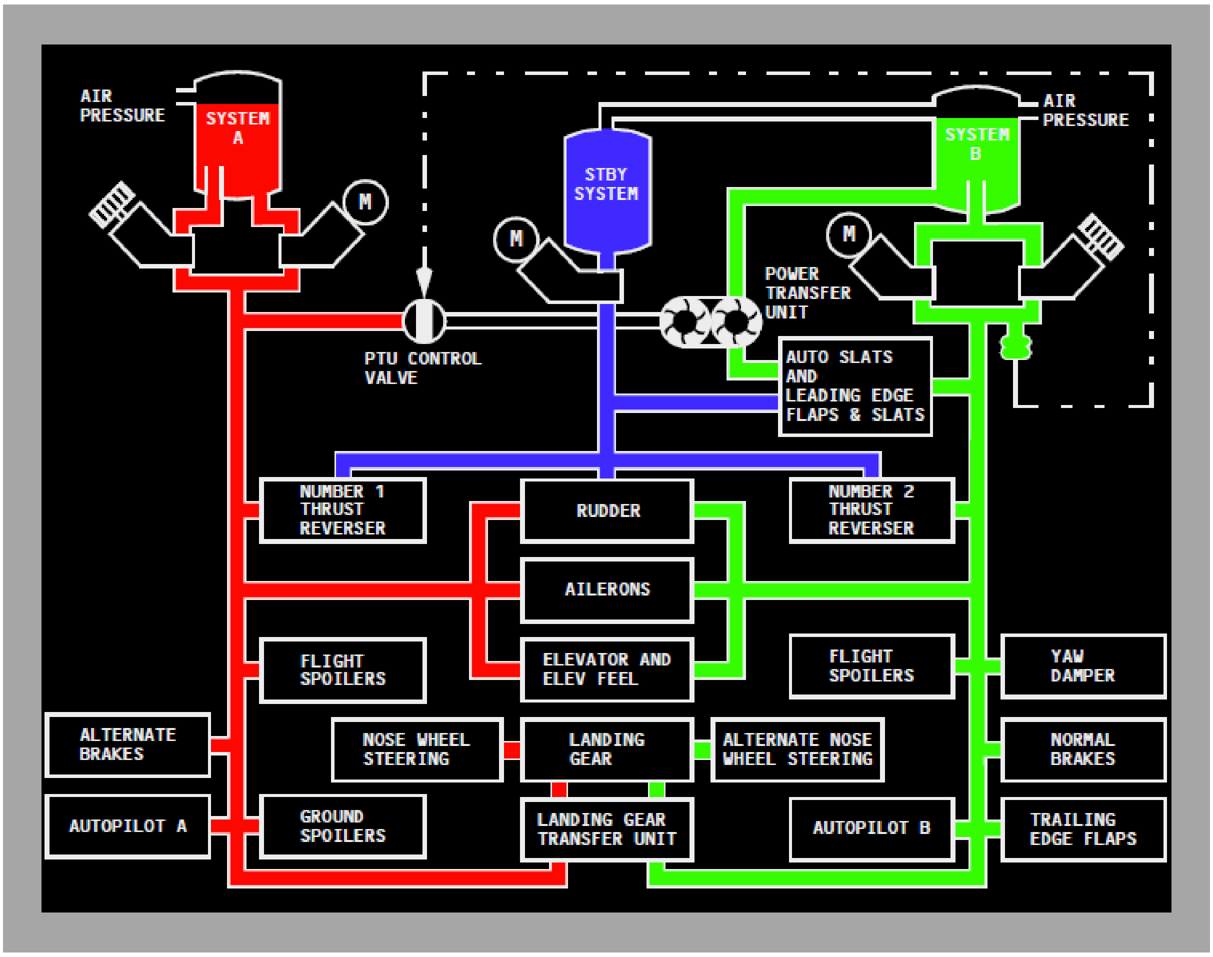


Figure B.8: Schematic overview of the hydraulic system on the Boeing 737-8 [35]

Autopilot A is no longer available, and hence, any procedures where dual autopilot redundancy is required were no longer possible, which was not a constraint in the scenario. Special consideration should be paid to the increase in landing distance due to inoperative flight spoilers (two on each wing), ground spoilers, alternate brakes, engine 1 thrust reverser, and normal nose wheel steering. Additionally, the landing gear had to be lowered manually, increasing deployment time. Also, the landing gear could not be retracted once extended. This imposes a drag penalty which may make reaching an alternate field in this scenario impossible. As such, the airport of choice is one of full commitment, leaving little room for misjudgment. As such, committing to destination alternate, where only one approach (RNAV) was available, is a more risky option. The planned destination, on the other hand, had plenty of options (three separate ILS approaches). Moreover, it was commercially attractive to fly to the planned destination. Therefore, the best option in the hydraulic leak failure scenario was to continue to the planned destination.

C
Drive Shaft Failure Checklists

This appendix presents all checklists from the Boeing 737-8 QRH [34] for the drive shaft failure. The blue dots indicate the correct progress of the checklist as per the scenario.

ANTISKID INOP

ANTISKID INOPERATIVE

Condition: An antiskid system fault occurs.

Caution! Locked wheel protection is not available.

1 AUTO BRAKE select switch. . . . . OFF

The autobrake system is inoperative.

2 Do **not** arm the speedbrakes for landing. Manually deploy the speedbrakes immediately upon landing.

Automatic speedbrake extension may be inoperative.

3 Check the Non–Normal Configuration Landing Distance table in the Advisory Information section of the Performance Inflight chapter.

4 **Checklist Complete Except Deferred Items**

Deferred Items

Landing Procedure Review

Use minimum braking consistent with runway length and conditions to reduce the possibility of a tire blowout.

Do **not** apply the brakes until the nose wheel is on the ground and the speedbrakes have been manually deployed.

▼ Continued on next page ▼

▼ANTISKID INOPERATIVE continued▼

Brake initially using light steady pedal pressure. Increase pressure as ground speed decreases. Do **not** pump the brakes.

Descent Checklist

Pressurization. . . . . LAND ALT ___

Recall . . . . Checked

Autobrake . . . . **OFF**

Landing data . . . . VREF ___, Minimums ___

Approach briefing . . . . Completed

Approach Checklist

Altimeters . . . . ___

Landing Checklist

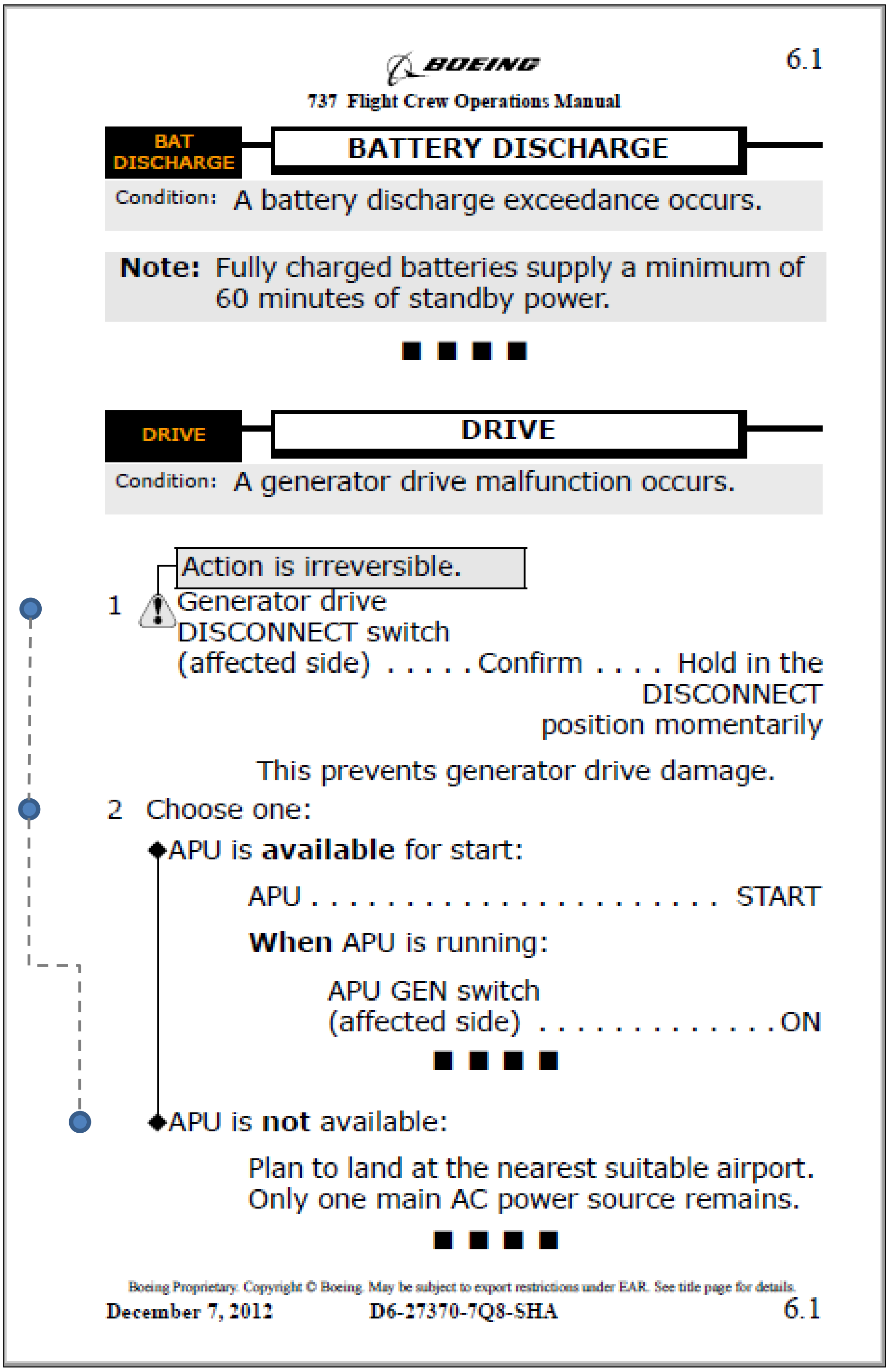
ENGINE START switches. . . . . CONT

Speedbrake . . . . **DOWN detent**

Landing gear . . . . Down

Flaps . . . . ___, Green light

■ ■ ■ ■



BOEING 6.1

737 Flight Crew Operations Manual

BAT DISCHARGE

BATTERY DISCHARGE

Condition: A battery discharge exceedance occurs.

Note: Fully charged batteries supply a minimum of 60 minutes of standby power.

■ ■ ■ ■

DRIVE

DRIVE

Condition: A generator drive malfunction occurs.

Action is irreversible.

1 Generator drive DISCONNECT switch (affected side) . . . . . Confirm . . . . Hold in the DISCONNECT position momentarily

This prevents generator drive damage.

2 Choose one:

◆APU is **available** for start:

APU . . . . START

When APU is running:

APU GEN switch (affected side) . . . . ON

■ ■ ■ ■

◆APU is **not** available:

Plan to land at the nearest suitable airport. Only one main AC power source remains.

■ ■ ■ ■

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December 7, 2012 D6-27370-7Q8-SHA 6.1

LOW PRESSURE

FUEL PUMP LOW PRESSURE

Condition: The fuel pump pressure is low.

Note: Fuel pump LOW PRESSURE lights may flicker when tank quantity is low and the airplane is in turbulent air or during climb or descent.

1 Choose one:

◆**One main** tank fuel pump LOW PRESSURE light is illuminated:

Main tank FUEL PUMP switch (affected pump). . . . . OFF

Sufficient fuel pressure is available for normal operation.

■ ■ ■ ■

◆**Both main** tank fuel pump LOW PRESSURE lights are illuminated:

Note: At high altitude, thrust deterioration or engine flameout may occur.

■ ■ ■ ■

◆**One CTR** tank fuel pump LOW PRESSURE light is illuminated:

►►**Go to step 2**

◆**Both CTR** tank fuel pump LOW PRESSURE lights are illuminated:

►►**Go to step 5**

▼ Continued on next page ▼

▼FUEL PUMP LOW PRESSURE continued▼

2 CROSSFEED selector. . . . . Open

This prevents fuel imbalance.

3 CTR FUEL PUMP switch (affected side) . . . . . OFF

4 **When** the other CTR tank fuel pump LOW PRESSURE light illuminates:

CROSSFEED selector . . . . Close

Remaining CTR FUEL PUMP switch . . . . . . OFF

■ ■ ■ ■

Both CTR tank fuel pump LOW PRESSURE lights are illuminated

5 CTR FUEL PUMP switches (both). . . . . OFF

6 Fuel CONFIG alert may show with fuel in the center tank.

7 Center tank fuel is unusable. Main tank fuel may not be sufficient for the planned flight.

■ ■ ■ ■

Fuel Quantity Indication Inoperative

Condition: The fuel quantity indication is blank.

1 Enter and periodically update the manually calculated FUEL weight on the FMC PERF INIT page.

■ ■ ■ ■

LOW PRESSURE

HYDRAULIC PUMP LOW PRESSURE

Condition: The hydraulic pump pressure is low.

1 HYD PUMP switch (affected side) . . . . OFF

Note: Loss of an engine-driven hydraulic pump and a high demand on the system may result in an intermittent illumination of the LOW PRESSURE light for the remaining electric motor-driven hydraulic pump.

■ ■ ■ ■

OVERHEAT

HYDRAULIC PUMP OVERHEAT

Condition: The hydraulic pump temperature is high.

1 ELEC HYD PUMP switch (affected side) . . . . . OFF

Note: One pump supplies sufficient pressure for normal system operation.

■ ■ ■ ■

BOEING 3.3

737 Flight Crew Operations Manual

ICING P-CANCEL

ICING

B-2663

Condition: Ice is detected.

1 ENG ANTI–ICE switches (both). . . . . ON

■ ■ ■ ■

PROBE HEAT

CAPT PITOT	L ELEV PITOT	L ALPHA VANE	TEMP PROBE
F/O PITOT	R ELEV PITOT	R ALPHA VANE	AUX PITOT

Condition: One or more probe heats are failed.

● 1 Avoid icing conditions.

Note: Flight in icing conditions may result in erroneous flight instrument indications.

■ ■ ■ ■

September 18, 2008 D6-27370-7Q8-SHA 3.3

SOURCE OFF | **SOURCE OFF**

Condition: The transfer bus is not powered by the last selected source.

1 Choose one:

◆**Both** SOURCE OFF lights are illuminated:

►►**Go to the LOSS OF BOTH ENGINE DRIVEN GENERATORS checklist on page 6.2**

■ ■ ■ ■

◆**Only one** SOURCE OFF light is illuminated:

►►**Go to step 2**

2 Engine GEN switch (affected side) . . . . ON

3 Choose one:

◆SOURCE OFF light **extinguishes:**

■ ■ ■ ■

◆SOURCE OFF light **stays illuminated:**

►►**Go to step 4**

▼ Continued on next page ▼

▼SOURCE OFF continued▼

4 Choose one:

◆APU is **available** for start:

APU . . . . START

When APU is running:

APU GEN switch
(affected side) . . . . ON

►►**Go to step 5**

◆APU is **not** available:

Plan to land at the nearest suitable airport.
Only one main AC power source remains.

■ ■ ■ ■

5 Choose one:

◆SOURCE OFF light **extinguishes:**

■ ■ ■ ■

◆SOURCE OFF light **stays illuminated:**

Plan to land at the nearest suitable airport.
Only one main AC power source remains.

■ ■ ■ ■

TRANSFER BUS OFF

TRANSFER BUS OFF

Condition: The transfer bus is not energized.

1 Engine GEN switch (affected side) . . . . ON

2 Choose one:

◆TRANSFER BUS OFF light **extinguishes**:

■ ■ ■ ■

◆TRANSFER BUS OFF light **stays illuminated**:

►►**Go to step 3**

3 Choose one:

◆APU is **available** for start:

APU . . . . START

When APU is running:

APU GEN switch
(affected side) . . . . ON

■ ■ ■ ■

◆APU is **not** available:

Plan to land at the nearest suitable airport.
Only one main AC power source remains.

■ ■ ■ ■

OVERHEAT

WINDOW OVERHEAT

Condition: A window overheat occurs.

1 WINDOW HEAT switch (affected window) . . . OFF

2 **Wait** 2 - 5 minutes.

3 WINDOW HEAT switch (affected window) . . . .ON

4 Choose one:

◆Window OVERHEAT light **stays extinguished**:

Continue normal operation.

■ ■ ■ ■

◆Window OVERHEAT light **illuminates again**:

►►**Go to step 5**

5 WINDOW HEAT switch (affected window) . . . OFF

Limit airspeed to 250 knots maximum below 10,000 feet.

6 Pull both WINDSHIELD AIR controls. This vents conditioned air to the inside of the windshield for defogging.

■ ■ ■ ■

YAW DAMPER

YAW DAMPER

Condition: The yaw damper is disengaged.

1 YAW DAMPER switch . . . . OFF then ON

2 Choose one:

◆ YAW DAMPER light **extinguishes**:

■ ■ ■ ■

◆ YAW DAMPER light **stays illuminated**:

YAW DAMPER switch . . . . OFF

►► **Go to step 3**

3 Avoid areas of predicted moderate or severe turbulence. If turbulence is encountered and passenger comfort becomes affected, reduce airspeed and/or descend to a lower altitude.

4 Do not exceed flaps 30 if the crosswind exceeds 30 knots.

■ ■ ■ ■

D
Hydraulic Leak Failure Checklists

This appendix presents all checklists from the Boeing 737-8 QRH [34] for the hydraulic leak failure. The blue dots indicate the correct progress of the checklist as per the scenario.

LOW PRESSURE

FLIGHT CONTROL LOW PRESSURE

Condition: Hydraulic system pressure to the ailerons, elevators and rudder is low.

Objective: To activate the standby hydraulic system and standby rudder PCU.

1 FLT CONTROL switch
(affected side) . . . . . . Confirm. . . . . .STBY RUD

■ ■ ■ ■

Jammed or Restricted Flight Controls

Condition: A flight control is jammed or restricted in roll, pitch, or yaw.

1 Autopilot (if engaged) . . . . .Disengage

2 Autothrottle (if engaged) . . . . .Disengage

3 Verify that the thrust is symmetrical.

4 Overpower the jammed or restricted system. Use maximum force, including a combined effort of both pilots, if needed. A maximum two-pilot effort on the controls will not cause a cable or system failure.

5 Do **not** turn off any flight control switches.

▼ Continued on next page ▼

LOW PRESSURE

HYDRAULIC PUMP LOW PRESSURE

Condition: The hydraulic pump pressure is low.

1 HYD PUMP switch (affected side) . . . . OFF

Note: Loss of an engine-driven hydraulic pump and a high demand on the system may result in an intermittent illumination of the LOW PRESSURE light for the remaining electric motor-driven hydraulic pump.

■ ■ ■ ■

OVERHEAT

HYDRAULIC PUMP OVERHEAT

Condition: The hydraulic pump temperature is high.

1 ELEC HYD PUMP switch (affected side) . . . . . OFF

Note: One pump supplies sufficient pressure for normal system operation.

■ ■ ■ ■

LOSS OF SYSTEM A

FLT CONTROL

A

LOW PRESSURE

A HYD PUMPS

ENG 1 ELEC 2

LOW PRESSURE LOW PRESSURE

Condition: Hydraulic system A pressure is low.

1 System A
FLT CONTROL switch. . . . Confirm . . . .STBY RUD

2 System A
HYD PUMP switches (both). . . . . OFF

3 Check the Non-Normal Configuration Landing Distance table in the Advisory Information section of the Performance Inflight chapter.

4 NOSE WHEEL STEERING switch . . . . ALT

5 Plan for manual gear extension.

Note: When the gear has been lowered manually, it cannot be retracted. The drag penalty with gear extended may make it impossible to reach an alternate field.

▼ Continued on next page ▼

▼LOSS OF SYSTEM A continued▼

Note: Inoperative Items

Autopilot A inop
Autopilot B is available.

Flight spoilers (two on each wing) inop
Roll rate and speedbrake effectiveness may be reduced in flight.

Normal landing gear extension and retraction inop
Manual gear extension is needed.

Ground spoilers inop
Landing distance will be increased.

Alternate brakes inop
Normal brakes are available.

Engine 1 thrust reverser normal hydraulic pressure inop
Thrust reverser will deploy and retract at a slower rate and some thrust asymmetry can be anticipated during thrust reverser deployment.

Normal nose wheel steering inop
Alternate nose wheel steering is available.

6 **Checklist Complete Except Deferred Items**

Deferred Items

Descent Checklist

Pressurization. . . . . LAND ALT ___

Recall . . . . Checked

Autobrake . . . . ___

Landing data . . . . VREF ___, Minimums ___

▼ Continued on next page ▼

▼LOSS OF SYSTEM A continued▼

Approach briefing . . . . Completed

Approach Checklist

Altimeters . . . . ____

Manual Gear Extension

LANDING GEAR lever. OFF

Manual gear extension handles. . . . . Pull

The uplock is released when the handle is pulled to its limit.

The related red landing gear indicator light illuminates, indicating uplock release.

Wait 15 seconds after the last manual gear extension handle is pulled:

LANDING GEAR lever . . . . .DN

Landing Checklist

ENGINE START switches. . . . . .CONT

Speedbrake . . . . .ARMED

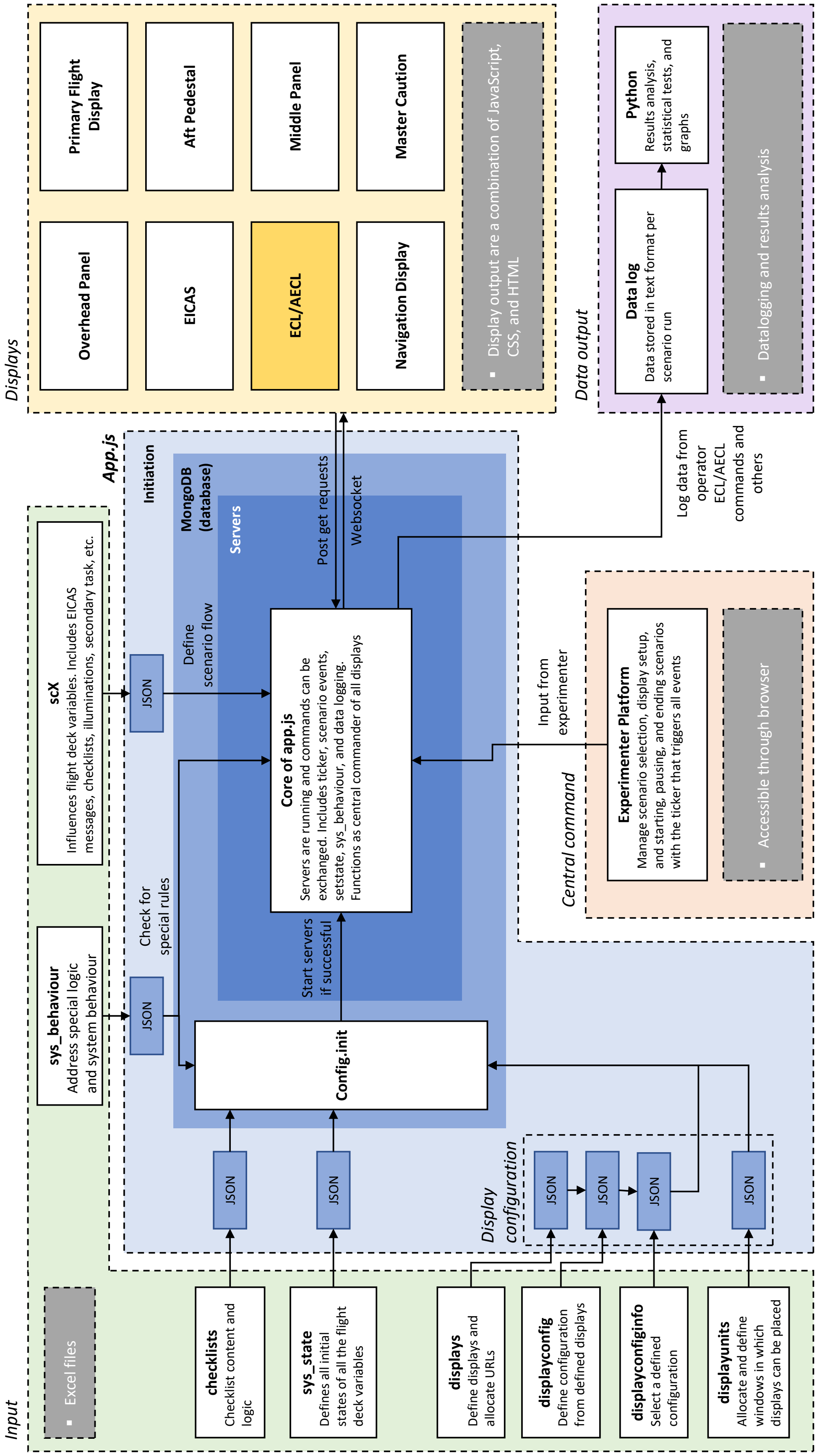
Landing gear . . . . .Down

Flaps . . . . ____, Green light

■ ■ ■ ■

E

Software Schematic



Displays
Primary Flight Display
Aft Pedestal
Middle Panel
Master Caution
Overhead Panel
EICAS
ECL/AECL
Navigation Display
Display output are a combination of JavaScript, CSS, and HTML
Data output
Data log
Data stored in text format per scenario run
Python
Results analysis, statistical tests, and graphs
Datalogging and results analysis
App.js
Initiation
MongoDB (database)
Servers
Post get requests
Websocket
Log data from operator ECL/AECL commands and others
scX
Influences flight deck variables. Includes EICAS messages, checklists, illuminations, secondary task, etc.
JSON
Define scenario flow
Core of app.js
Servers are running and commands can be exchanged. Includes ticker, scenario events, setstate, sys_behaviour, and data logging. Functions as central commander of all displays
Input from experimenter
Central command
Experimenter Platform
Manage scenario selection, display setup, and starting, pausing, and ending scenarios with the ticker that triggers all events
Accessible through browser
sys_behaviour
Address special logic and system behaviour
Check for special rules
Start servers if successful
Config.init
Display configuration
Input
Excel files
checklists
Checklist content and logic
sys_state
Defines all initial states of all the flight deck variables
displays
Define displays and allocate URLs
displayconfig
Define configuration from defined displays
displayconfiginfo
Select a defined configuration
displayunits
Allocate and define windows in which displays can be placed

F
Experiment Invitation

Invitation to participate in the ECL experiment

In short…

- The research aims at developing a novel improved version of the **Electronic Checklist** (ECL)
- The ECL is specifically developed for a B737 cockpit and its systems. As such, the research team is **looking for enthusiastic B737 pilots** to participate in the experiment!
- Participation comprises the **execution of two scenarios** in which you will be **challenged** to best test the display's competence

- *The experiment is the conclusion of a 9-month research project in the context of my (Coen Linskens) MSc thesis*
- *For any questions, please don't hesitate to contact me*

Participate?

- The experiment is conducted at the TU Delft Aerospace Engineering facilities (see contact details)
- Experiments will commence in the first week of June
- The duration of the experiment is c. 2 hours
- Please click the link below to schedule a session!

https://doodle.com/meetme/qc/AcqyQqqtJ

NOTE: In regards to COVID-19 measures, participation is only allowed if you can travel by private transport. Hence, having to rely on public transportation to participate in the experiment is unfortunately not allowed.

Appropriate measures are taken on location concerning COVID-19

The specially created cockpit (in development), fully functional with touch screens (including the overhead)!

Contact:
Coen Linskens
E: coenlinskens@live.nl
M: +31642847485
Locatie: Kluyverweg 1, 2629 HS Delft (faculty of Aerospace Engineering, TU Delft)

TU Delft

G
Experiment Consent Form

Consent Form

Consent Form for ECL Experiment

Please tick the appropriate boxes

Taking part in the study:

	YES	NO
I have read and understood the study information dated 9/15/2020, or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	○	○
I understand that taking part in the study involves having performance data automatically stored in an anonymous manner when completing the experiment.	○	○
I understand that taking part in the study involves me answering questions to surveys.	○	○
I understand that taking part in the study involves having video recordings stored of the experiment. Video recordings are stored and only accessible by the study team.	○	○
I understand that taking part in the study involves being subjected to stressful situations.	○	○

Use of the information in the study:

	YES	NO
I understand that information I provide will be used for in the paper and thesis report on an anonymous basis.	○	○
I understand that personal information collected about me that can identify me, such as my name, email address, and phone number, will not be shared beyond the study team. *The study team does not aim to collect any personal information.*	○	○
I agree that my information can be quoted in research outputs on an anonymous basis. *The study team does not aim to collect any personal information.*	○	○

Future use and reuse of the information by others:

	YES	NO
I give permission for the recorded performance data, answers to surveys, and video recordings, that I provide to be archived in secure folders so it can be used for future research and learning. All data is stored anonymous. Access is safeguarded and not to be used for commercial use. *The study team does not aim to collect any personal information.*	○	○

Health Risks:

	YES	NO
I understand that the study team and the Delft University of Technology is not responsible for any mental and or physical damage incurred.	○	○
I understand that the study team and the Delft University of Technology is not responsible for any implications regarding COVID-19 despite the taken measures.	○	○

COVID-19:

	YES	NO
I confirm that the researcher has provided me with detailed safety instructions to ensure my experiment session can be performed in line with current RIVM COVID-19 regulations at all times and that these instructions are fully clear to me.	○	○
I understand that also for my travel to/from the experiment session I should at all times adhere to the current RIVM COVID-19 regulations. I confirm that I have travelled to TU Delft's Faculty of Aerospace Engineering with either my own car, by bicycle, or on foot.	○	○

Name of participant:

Signature of participant

× SIGN HERE

Date: 9/15/2020

Name of Researcher:

Coen Linskens

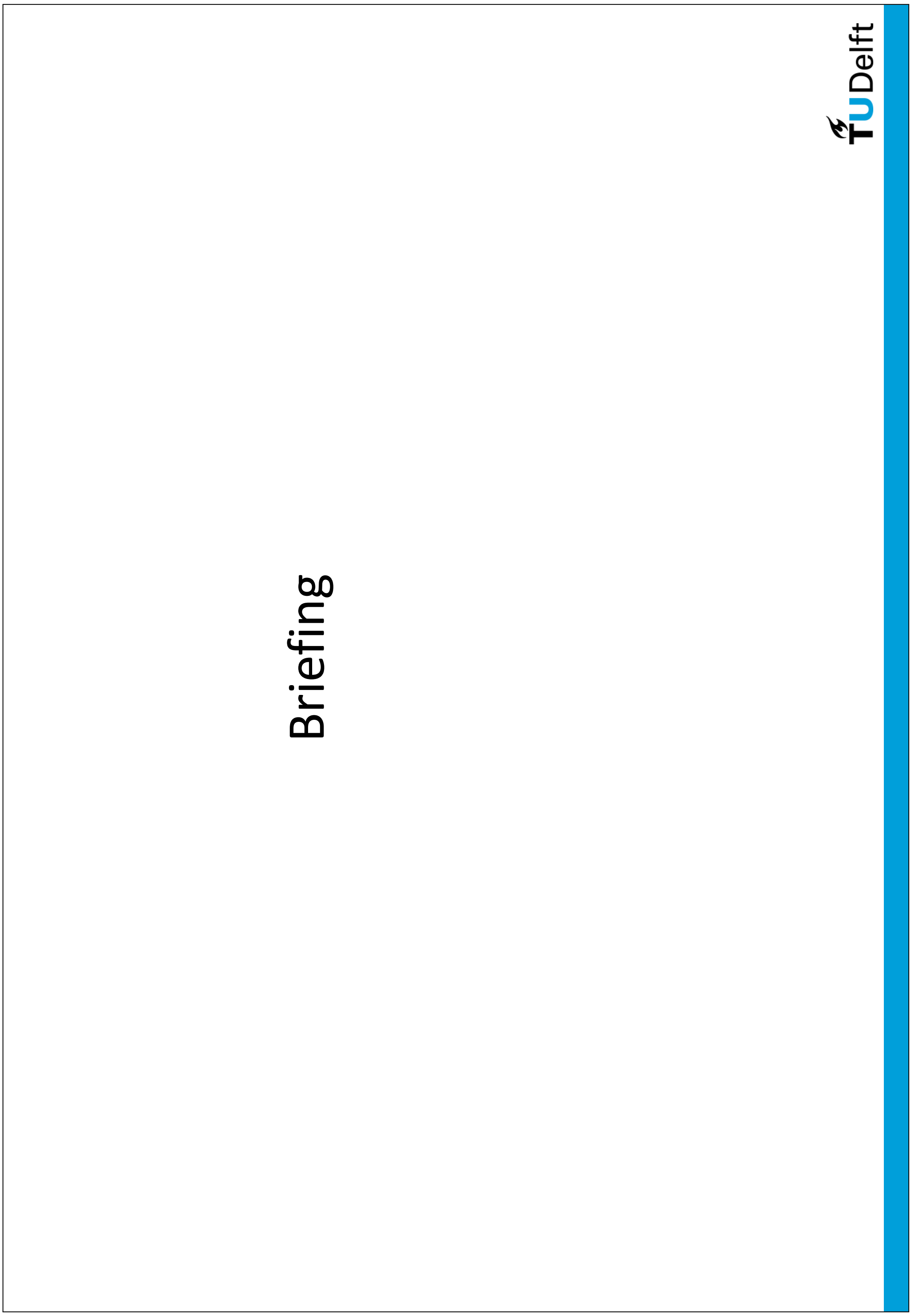
Signature of Researcher:

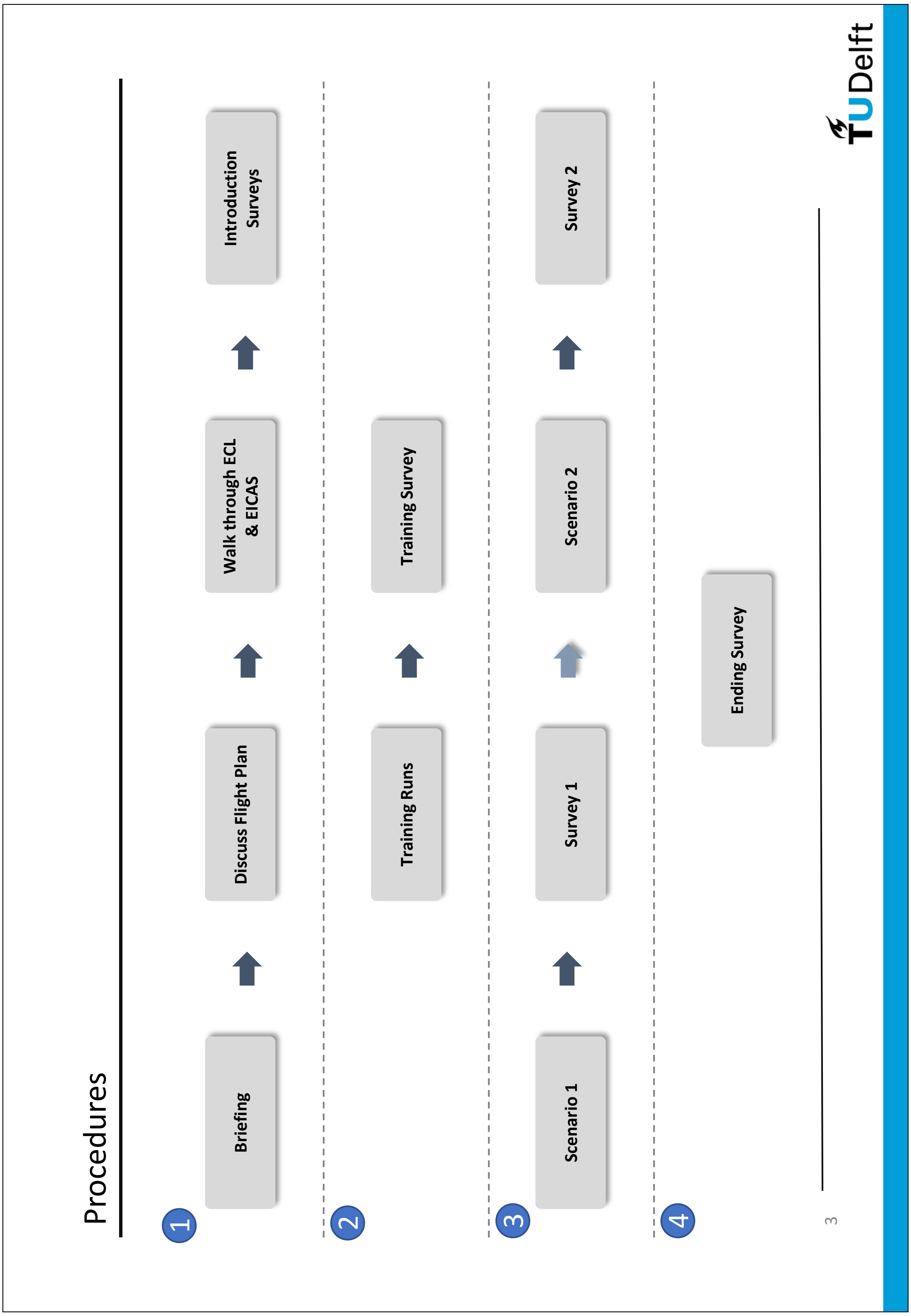
Date: 9/15/2020

H

Experiment Briefing


Briefing - Experiment
Part of Master of Science Thesis
by
C.E. Linskens
TU Delft


Briefing


Procedures
1
Briefing
Discuss Flight Plan
Walk through ECL & EICAS
Introduction Surveys
2
Training Runs
Training Survey
3
Scenario 1
Survey 1
Scenario 2
Survey 2
4
Ending Survey
3
TU Delft

Why This Experiment?

- The goal of the research is to develop an improved ECL aiming to lower the pilot workload and supporting situation awareness
- This is particularly relevant for non-normal events where workloads can *unexpectedly* peak and safety of operations is under the most pressure
- Proposed solutions for the above are through i) automation and ii) a more efficient manner of information sharing
- Hopefully, we can contribute to making your job safer and more manageable
- Two designs are tested during the experiment phase, the B787 ECL (base case) and the novel ECL
- You will be utilizing one of the above throughout the day

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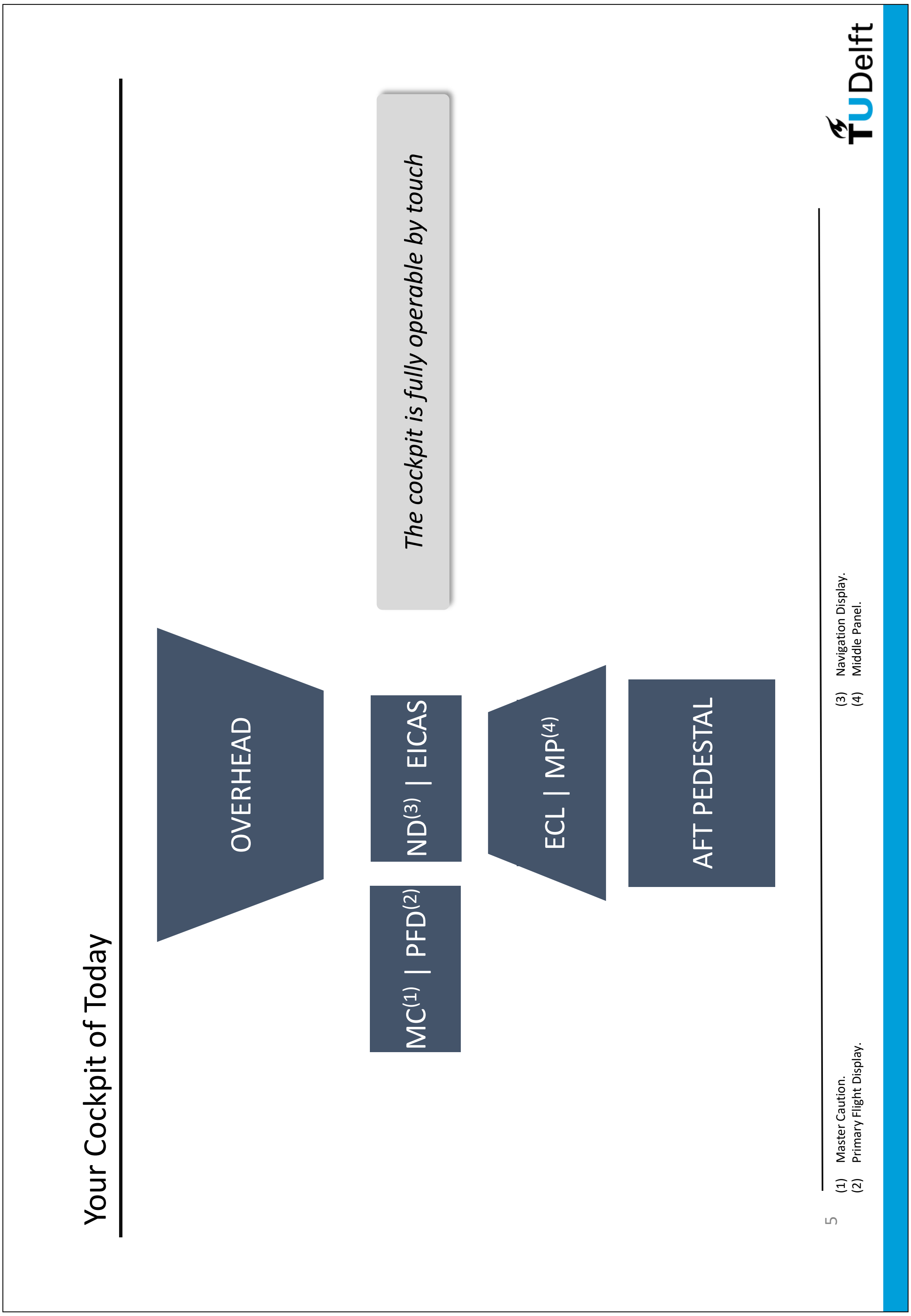
Your Cockpit of Today
OVERHEAD
MC(1) | PFD(2)
ND(3) | EICAS
ECL | MP(4)
AFT PEDESTAL
The cockpit is fully operable by touch
(1) Master Caution.
(2) Primary Flight Display.
(3) Navigation Display.
(4) Middle Panel.
5

Your Task for Today

Primary task

- You will be expected to complete your mission the best way possible according to your flight plan
- You are flying a B737-800 commercial airline from DUT[1] airlines
- If something occurs during a scenario, we ask you to assess the situation and create a plan of what to do next in terms of your mission. It is expected you handle this the same way as during your day-to-day job. For example, you might decide to decrease your altitude. Once you have constructed a plan and rationalized your decision, please indicate you have done so to the operator. The scenario will be stopped at that instance. Note that speed is not an objective in itself, however it is recorded as part of the experiment.
- You can **indicate** your **completion** with saying: **"I am done"** or **"ik ben kaar"**
- Note that this means we will not be landing the aircraft
- Note that only one-way ATC communication is present, and you are not expected to ask clearance etc. You can expect to be able to act on your plan of action (as within reasonable limits of course)
- You will start the mission at AST waypoint
- The autopilot engaged is A/P A
- Note that the initiation of every scenario utilizes the exact same values and settings throughout the cockpit

Secondary task

- ATC is actively communicating with various aircraft and might in some cases address yours
- Your task is to identify the message directed to you, which contains your callsign, and report back on the request
- Your report is required to be done verbally. The operator however will not be acknowledging your report (but is recorded)
- For example: "[Your callsign], please state your current airspeed: my True Airspeed is XX km/h"
- It is not relevant whether you indicate True/Ground Airspeed, km/h / mph / kts but that you indicate what you respond and in an accurate manner

(1) Delft University of Technology.

6

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I

Experiment Flight Plan

FLIGHT PLAN

UAAA	-	**USTR**
Almaty		*Roshchino*

10/08/2020

UAAA ETEDA DODOK RITAB TULPI BLH LUKUS BANOS AST BEBLU USTR

DEPARTURE DATE/TIME		**ARRIVAL DATE/TIME - INCLUDES TAXI TIME**	
10/10.05	(ZULU)	10/12.37	(ZULU)
10/16.05	(LOCAL)	10/17.37	(LOCAL)

AIRCRAFT

GENERAL			**WEIGHT (IN KG)**		
TYPE:	B738	LOAD IN COMPARTMENTS:	01704		
CALLSIGN:	DUT 961	PASSENGER/CABIN BAG:	09124		
MISSION		TOTAL TRAFFIC LOAD:	10828		
CRUIS ALT:	FL350	DRY OPERATING WEIGHT:	41077		
PAX:	87	ZERO FUEL WEIGHT ACTUAL:	51905	MAX	61689
EQUIP:	APU N/A	TAKE OFF FUEL:	11133		
		TAKE OFF WEIGHT ACTUAL:	63038	MAX	79016
		TRIP FUEL:	07105		
		LANDING WEIGHT ACTUAL:	55932	MAX	65319

ROUTE

CHKPNT	**LAT**	**LON**	**FL**	**LEG DIST (NM)**	**ELAP DIST (NM)**	**AVG WIND**
UAAA	43.212000	77.023800	000	0	0	3 KTS (HEADS)
ETEDA	44.202399	76.320599	225	63	63	
DODOK	45.141999	76.001099	350	59	122	
RITAB	45.430799	75.423899	350	31	153	
TULPI	46.131799	75.235799	350	33	186	
BLH	46.525940	74.590196	350	43	229	
LUKUS	48.075899	74.165799	350	80	309	
BANOS	50.111599	72.384399	350	139	448	
AST	51.000559	71.250039	350	67	515	
BEBLU	54.462999	66.502999	290	281	796	
USTR	57.100600	65.185800	000	163	959	

NOTE: ALTITUDES IN RUSSIA ARE REPORTED BY ATC IN FL

NOTAM

UAUU

DATA CURRENT AS OF: 10/09.50 (ZULU)

ILS RWY 12 OUT OF SERVICE. 08 AUGUST 08:20 (LOCAL) UNTIL 24 AUGUST 12:00 ESTIMATED
RWY 12 CLSD. 08 AUGUST 08:20 (LOCAL) UNTIL 24 AUGUST 12:00 ESTIMATED

DEPARTURE

UAAA

REGION:	KAZAKHSTAN AND KYRGYZSTAN	ELEVATION:	2,233 FT
TIMEZONE:	ASIA (UTC +6.0)	MAGNETIC VAR:	5.272 E
RUNWAYS:	4	LOCATION:	43.355500/ 77.043900

METAR: UAAA 100915Z 03008KT 9999 FEW048 15/05 Q1026 NOSIG

TAF: TAF UAAA 100530Z 1006/1106 08005KT 0600 PRFG BKN002 BECMG 1006/1007 CAVOK BECMG 1010/1012 02010KT

DESTINATION

USTR

REGION:	RUSSIA	ELEVATION:	377 FT
TIMEZONE:	ASIA (UTC +5.0)	MAGNETIC VAR:	15.149 E
RUNWAYS:	9	LOCATION:	57.179700/ 65.319500

METAR: USTR 100855Z 15008KT 110V190 9999 FEW028 18/11 Q1034 NOSIG

TAF: TAF USTR 100845Z 1010/1112 15007KT 9999 FEW018 BECMG 1016/1112 18010KT TEMPO 1101/1106 4000 MIFG BR BECMG 1105/1112 20006KT

RUNWAYS

IDENT	WIDTH	LENGTH	BEARING (TRUE/MAG)	SURFACE	TRESHOLD OFFSET	OVERRUN LENGTH	MARKINGS
03L	58 M	3662 M	40.48/28.07	ASPHALT	0 M	0 M	PREC-APP
03R	49 M	3874 M	43.10/30.70	ASPHALT	0 M	0 M	APP
06	46 M	1917 M	57.85/56.37	ASPHALT	248 M	0 M	APP
15L	48 M	3121 M	157.00/144.59	ASPHALT	0 M	0 M	PREC-APP
15R	45 M	3079 M	157.84/145.43	ASPHALT	0 M	0 M	APP
21	49 M	1808 M	223.11/210.70	ASPHALT	0 M	0 M	APP
33L	49 M	3368 M	337.85/325.44	ASPHALT	0 M	0 M	PREC-APP
33R	48 M	3119 M	337.01/324.60	ASPHALT	0 M	0 M	APP
36	60 M	3749 M	8.20/355.79	ASPHALT	396 M	0 M	VISUAL

APPROACH NAVAIDS

RUNWAY	TYPE	FREQUENCY	RANGE	BEARING (TRUE/MAG)	SLOPE	ELEVATION
03L	DME	110.55 MHz	18 NM	-	-	377 FT
03L	LOC-ILS	110.55 MHz	18 NM	40.48/28.07	-	377 FT
03L	GS	110.55 MHz	10 NM	40.48/28.07	3.00	377 FT
15L	DME	108.65 MHz	18 NM	-	-	377 FT
15L	LOC-ILS	108.65 MHz	18 NM	157.01/144.60	-	377 FT
15L	GS	108.65 MHz	10 NM	157.01/144.60	3.00	377 FT
33L	DME	111.35 MHz	18 NM	-	-	377 FT
33L	LOC-ILS	111.35 MHz	18 NM	337.01/324.60	-	377 FT
33L	GS	111.35 MHz	10 NM	337.01/324.60	3.00	377 FT

NOTE: NO VISUAL OR CIRCLING APPROACHES ALLOWED UFN.

DESTINATION ALTERNATE

UAUU

REGION:	KAZAKHSTAN AND KYRGYZSTAN	ELEVATION:	600 FT
TIMEZONE:	ASIA (UTC +6.0)	MAGNETIC VAR:	12.407 E
RUNWAYS:	3	LOCATION:	53.2066/ 63.5434

METAR: UAUU 100920Z 36010KT 330V040 9999 FEW038 19/10 Q1033 NOSIG

TAF: TAF UAUU 100800Z 1009/1111 33010KT 9999 SCT040 BECMG 1017/1019 36005KT BECMG 1021/1024 VRB03KT BECMG 1108/1111 01006KT

RUNWAYS

IDENT	WIDTH	LENGTH	BEARING (TRUE/MAG)	SURFACE	TRESHOLD OFFSET	OVERRUN LENGTH	MARKINGS
03L	50 M	3668 M	47.64/32.49	ASPHALT	0 M	0 M	PREC-APP
03R	46 M	3450 M	47.63/32.48	ASPHALT	0 M	0 M	PREC-APP
12	44 M	3749 M	137.67/122.52	ASPHALT	0 M	0 M	PREC-APP

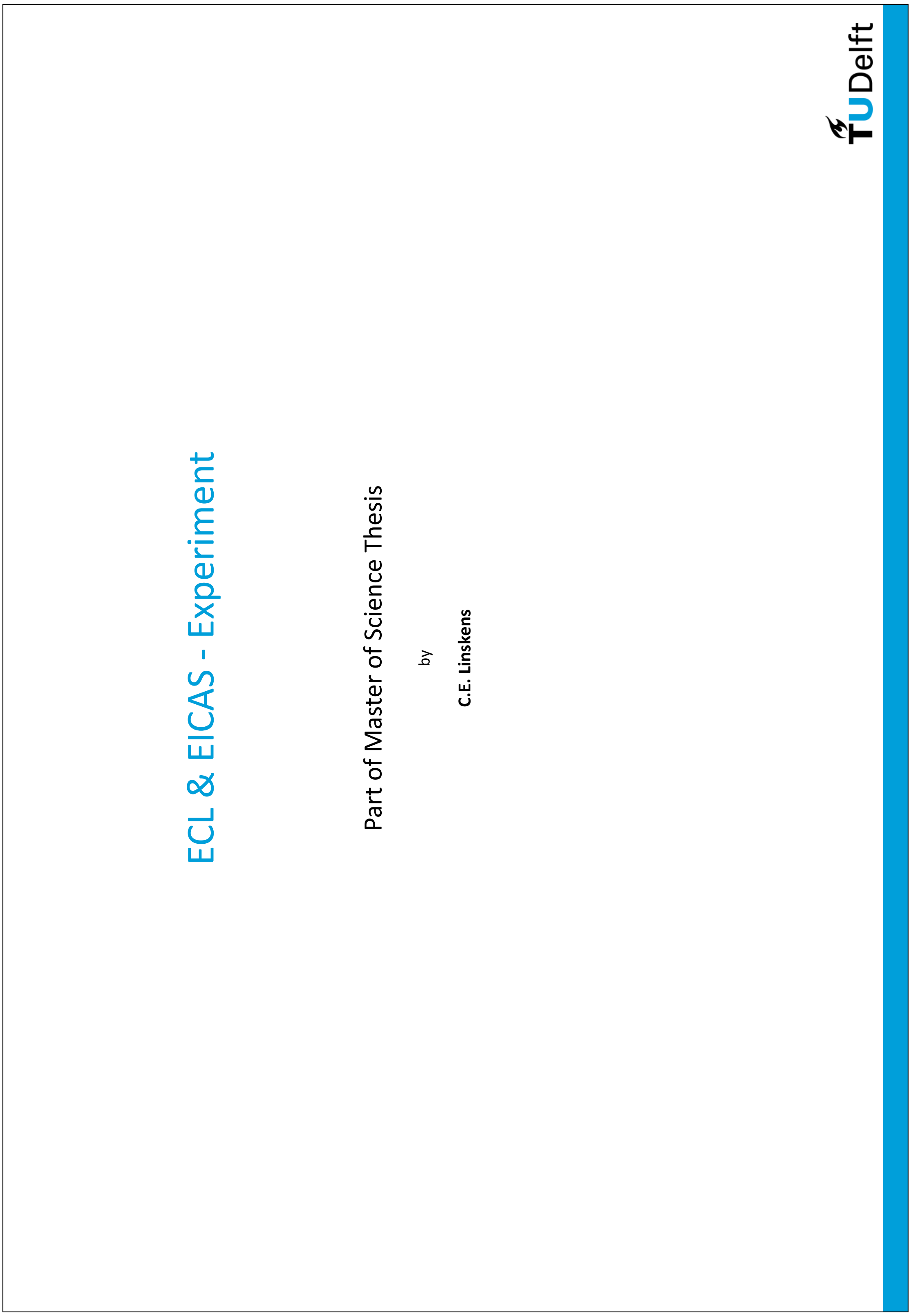
APPROACH NAVAIDS

RUNWAY	TYPE	FREQUENCY	RANGE	BEARING (TRUE/MAG)	SLOPE	ELEVATION
03L	RNAV	110.30 MHz	18 NM	47.99/32.84	-	600 FT
12	LOC-ILS	108.30 MHz	18 NM	137.99/122.84	-	600 FT
12	GS	108.30 MHz	10 NM	138.00/122.85	3.00	600 FT

NOTE: NO VISUAL OR CIRCLING APPROACHES ALLOWED UFN.

J

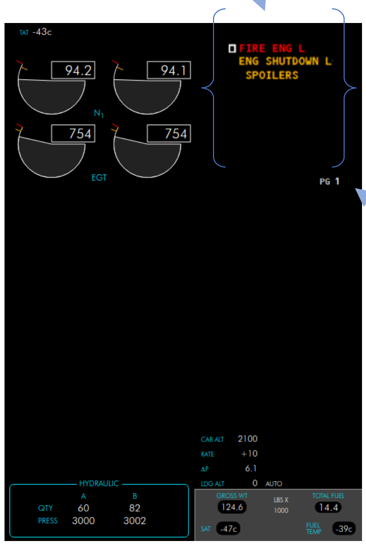
EICAS and ECL Display Instructions


ECL & EICAS - Experiment
Part of Master of Science Thesis
by
C.E. Linskens
TU Delft

EICAS

EICAS

Messages will appear here



Active page

In today's cockpit, hydraulic information is shown here

- Today's 'adaption' of the Boeing 737-800 can automatically detect some of the system states in the aircraft – just like in for example the B777 or B787
- Once an error/fault/malfunction in such state is detected, an according message is communicated to the pilot through EICAS
- This is in addition to the illumination of associated lights in the cockpit, the master caution and the '6-pack' (1)
- Whenever a message has an associated checklist which is still *incomplete*, a white box is present in front of the message
- Red messages are warnings, amber non-indent messages are cautions, and amber indent messages are advisories.
- Also white messages may appear, which are communication or memo messages.
- In case of multiple messages, EICAS might get multiple pages. Your current page is indicated below on the right of the messages

(1) Note that the 6-pack is not present in today's cockpit.

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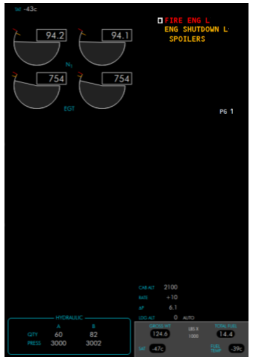
EICAS and MASTER CAUTION



- In case of a warning or a caution, the master caution will illuminate. Today we have only the left-side master caution
- In case of the sounding of the autopilot horn, the warning master caution button (which is now illuminated) can be pressed, ending the sounding of the horn. If available, the other autopilot can be connected through the MCP. Note that the MCP is not ‘active’, but whether the required action occurs will still be registered
- To handle multiple pages on EICAS, the CANC / RCL button can be pressed. For example, when having two pages:
  - Pressing once will show the second page
  - Pressing twice will (if relevant) only show the warning message
  - Pressing again will show the first page again

(1) Note that the 6-pack is not present in today’s cockpit.

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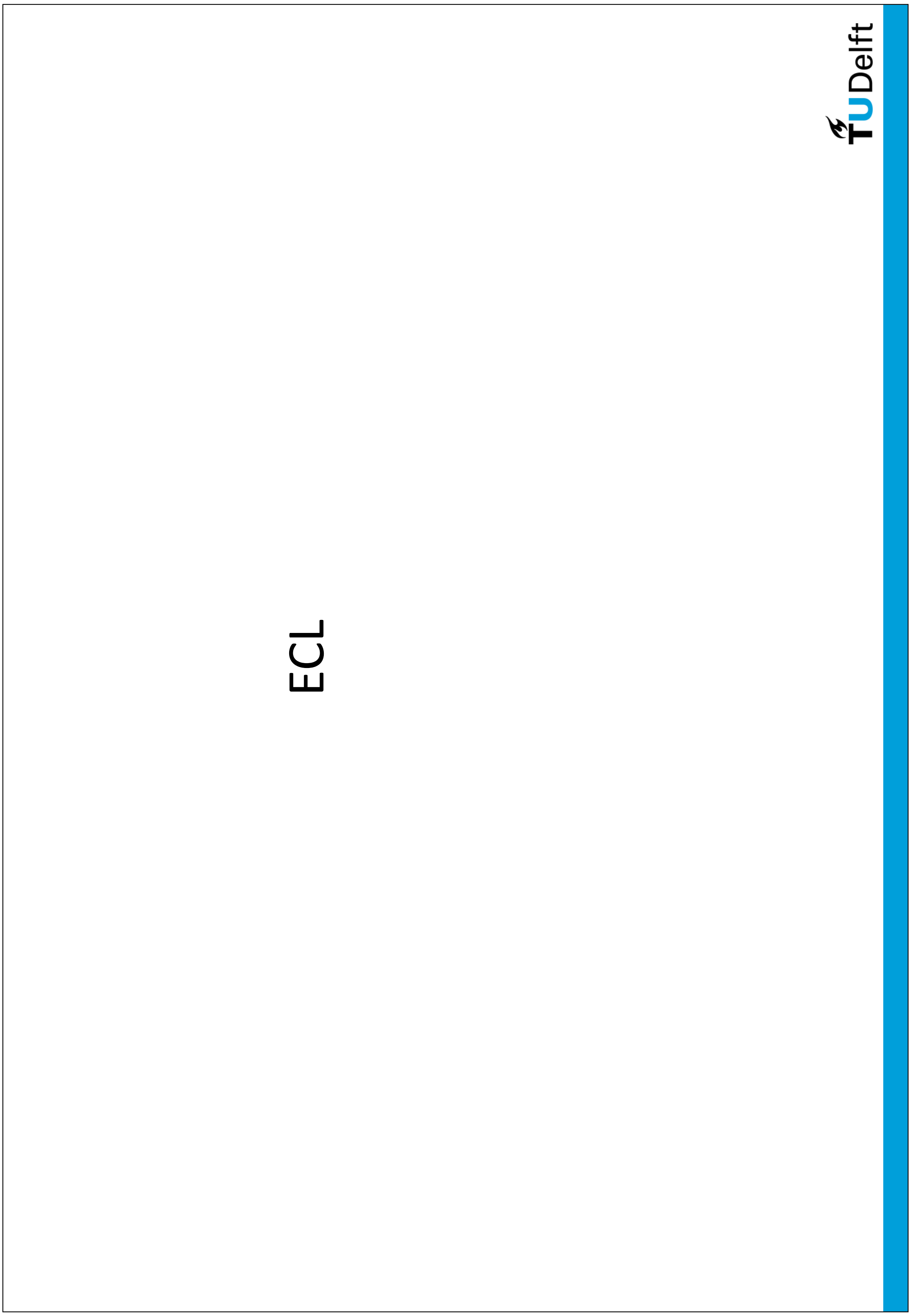
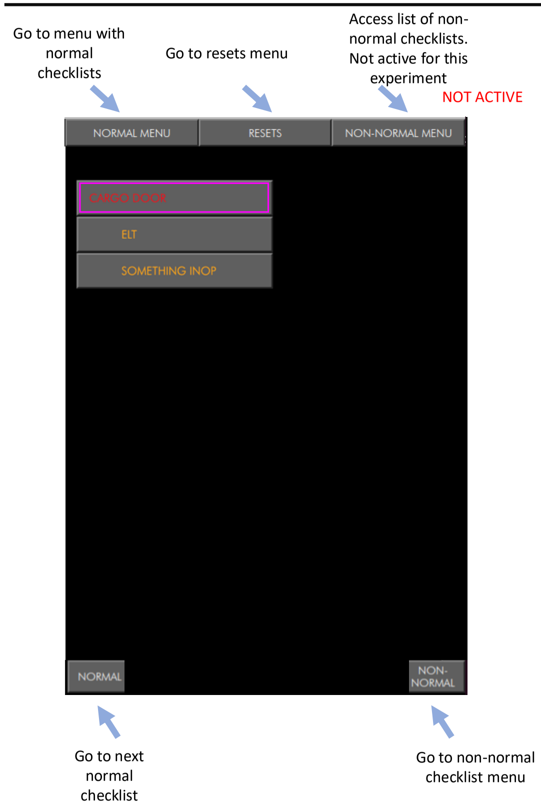

ECL

ECL

ECL menu and navigation



- After EICAS reports an incomplete checklist is available, this checklist will appear on the ECL
- In case of a single incomplete checklist, this checklist will automatically be opened
- Whenever more checklists become available, you can navigate to the menu (as shown on the left) by pressing the bottom-right non-normal button
- The result of having multiple checklists within the ECL abnormal menu is shown on the left
- They are ranked based on Warning, Caution, and Advisory
- Within these categories, the messages show up in order of occurrence
- The pilot can select the checklist (indicated with pink box), after which the checklist is opened (see next slide)
- Please note that you can select any checklist at your own choosing. You are not restricted to the order of messages

- Today's aircraft can sense system states. If this is the case, such step is called a 'closed loop' step. These steps will be automatically administered by the ECL
- 'Open loop' steps on the other hand require manual confirmation by the pilot

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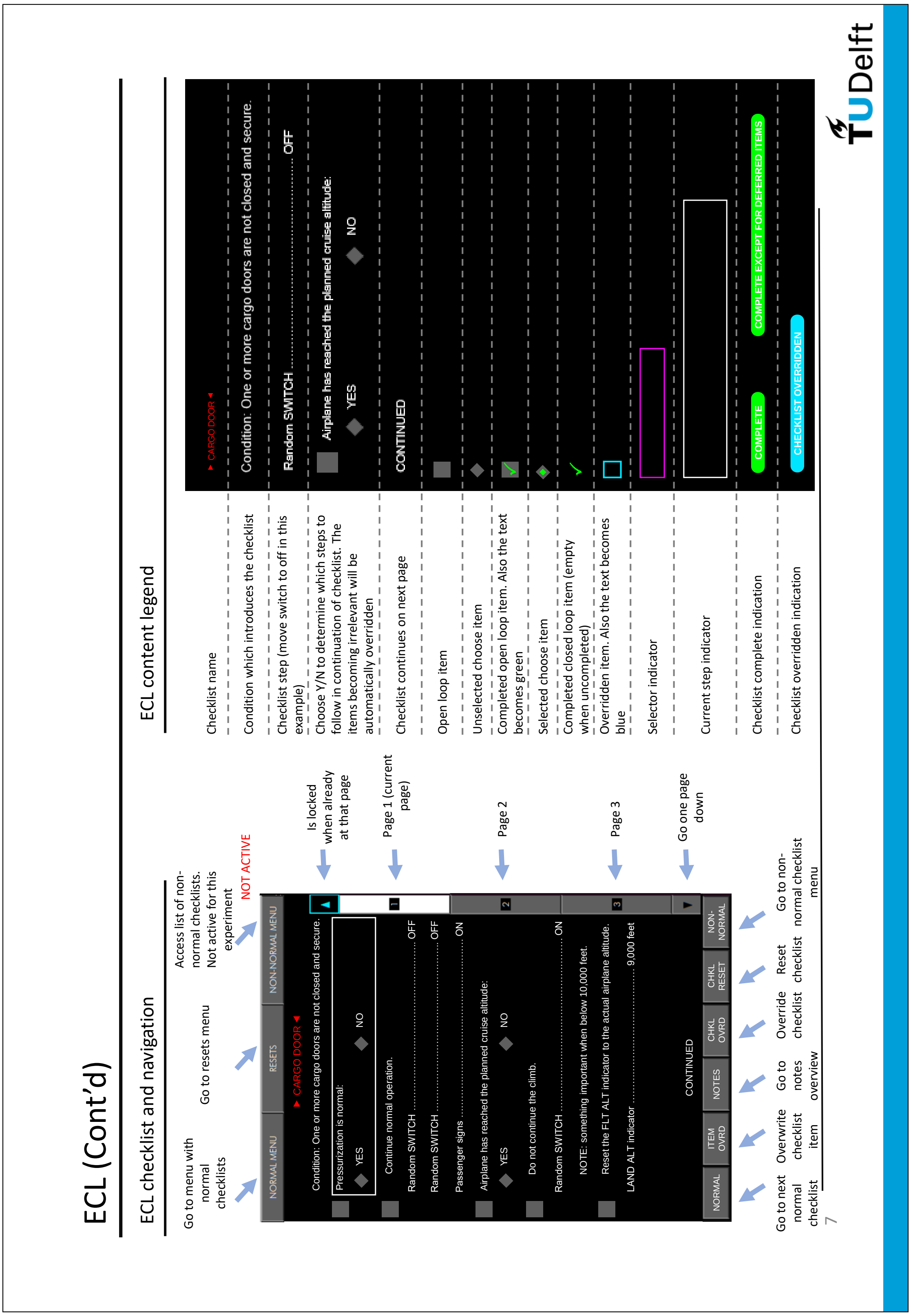
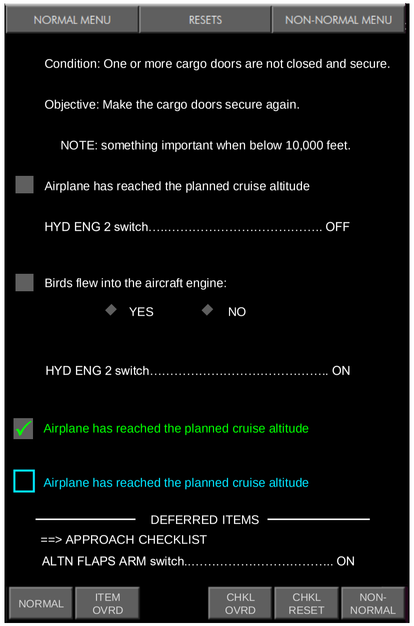

ECL (Cont'd)
ECL checklist and navigation
Go to menu with normal checklists
Go to resets menu
Access list of non-normal checklists. Not active for this experiment
NOT ACTIVE
NORMAL MENU
RESETS
NON-NORMAL MENU
CARGO DOOR
Condition: One or more cargo doors are not closed and secure.
Pressurization is normal:
YES
NO
Continue normal operation.
Random SWITCH .... OFF
Random SWITCH .... OFF
Passenger signs .... ON
Airplane has reached the planned cruise altitude:
YES
NO
Do not continue the climb.
Random SWITCH .... ON
NOTE: something important when below 10,000 feet.
Reset the FLT ALT indicator to the actual airplane altitude.
LAND ALT indicator .... 9,000 feet
CONTINUED
NORMAL
ITEM OVRD
NOTES
CHKL OVRD
CHKL RESET
NON-NORMAL
Is locked when already at that page
Page 1 (current page)
Page 2
Page 3
Go one page down
Go to next normal checklist
Overwrite checklist item
Go to notes overview
Override checklist
Reset checklist
Go to non-normal checklist menu
7
ECL content legend
Checklist name
CARGO DOOR
Condition which introduces the checklist
Condition: One or more cargo doors are not closed and secure.
Checklist step (move switch to off in this example)
Random SWITCH .... OFF
Choose Y/N to determine which steps to follow in continuation of checklist. The items becoming irrelevant will be automatically overridden
Airplane has reached the planned cruise altitude:
YES
NO
Checklist continues on next page
CONTINUED
Open loop item
Unselected choose item
Completed open loop item. Also the text becomes green
Selected choose item
Completed closed loop item (empty when uncompleted)
Overridden item. Also the text becomes blue
Selector indicator
Current step indicator
Checklist complete indication
COMPLETE
COMPLETE EXCEPT FOR DEFERRED ITEMS
Checklist overridden indication
CHECKLIST OVERRIDDEN
TU Delft

Type of Steps You Might Encounter in the ECL

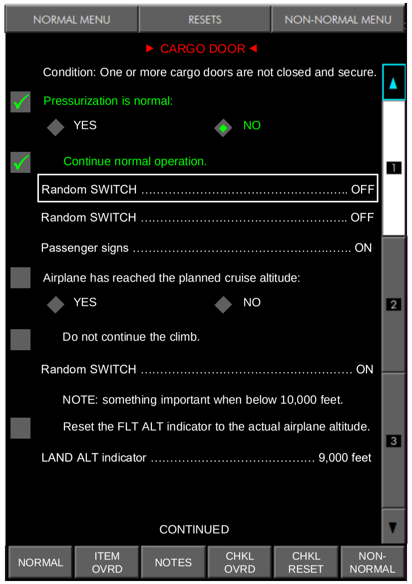


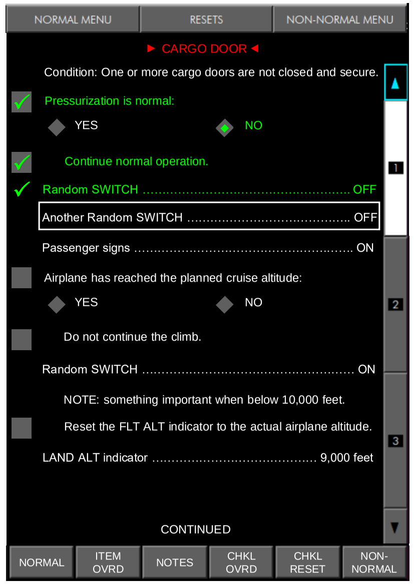
1. Condition
2. Objective
3. Note
4. Open loop step
5. Closed loop step
6. Choose step. Can be both open loop or closed loop. Special case is sequence dependent closed loop. For example: "XYZ stays illuminated:". This step only can be performed once the previous steps are completed.
7. A repetition of the same closed loop item but with a different required position. In this case the previous 'double' item gets automatically overridden
8. Completed step
9. Overridden step
10. Deferred Item

8

TUDelft

The Process of Completing a Checklist



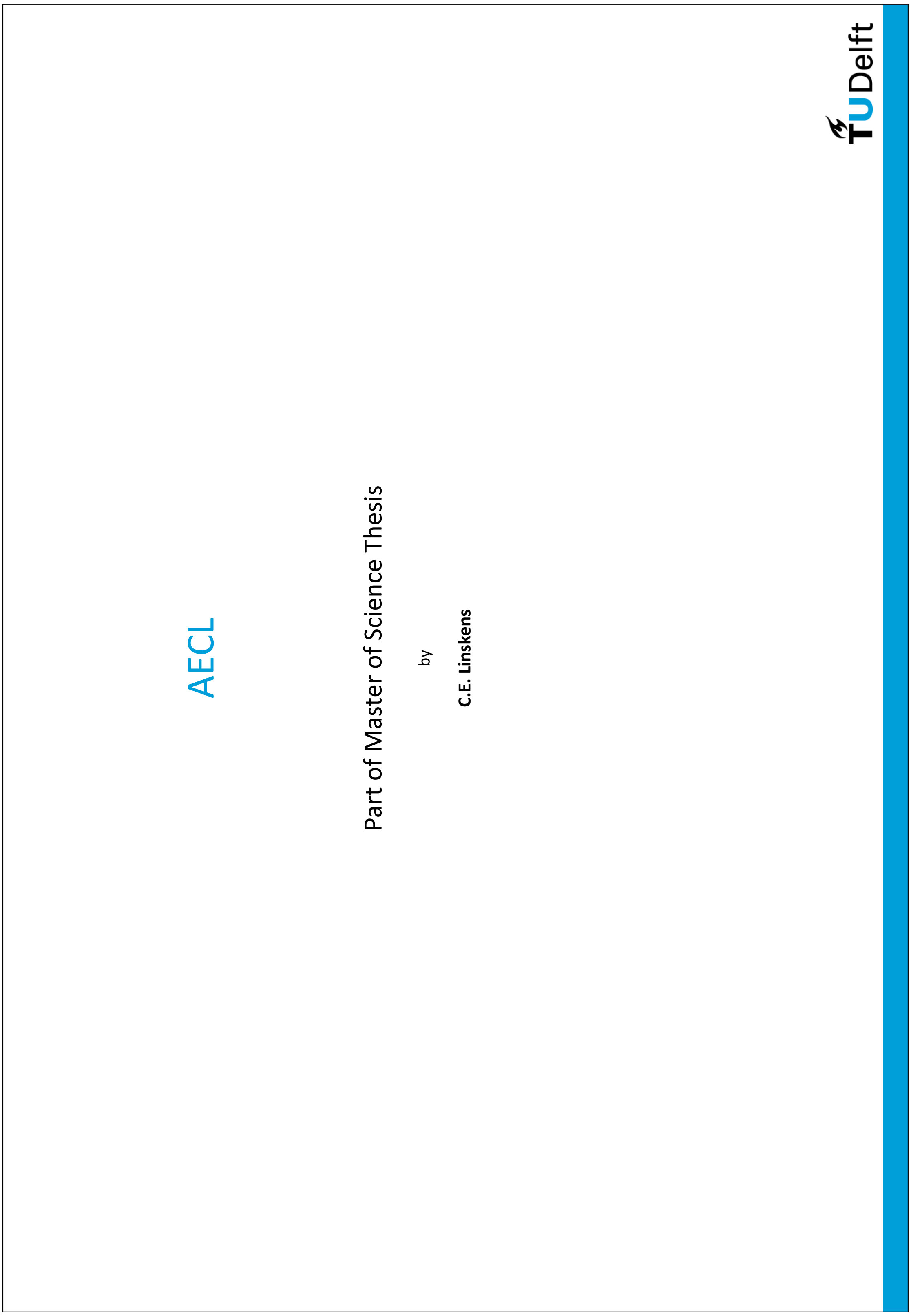


- Once a checklist is completed, completed except for deferred items, or overridden, and you leave the checklist; it will disappear from the menu, no white box is present before the EICAS message, the notes are listed in the NOTES page and the deferred items are listed in their respective normal checklist
- Additionally, once every step on a page is completed, the page number becomes green
- Note that you can only see the green checklist completed box once you are on the last page of the checklist

9

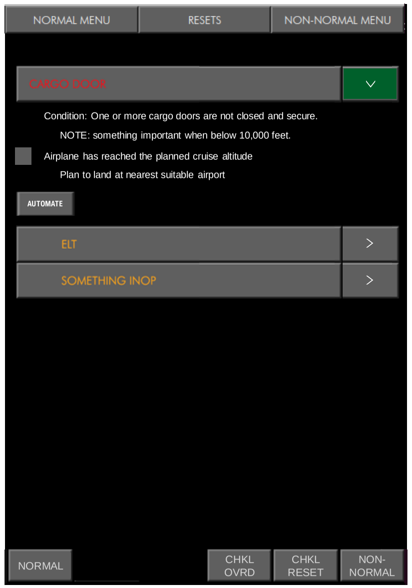
K

AECL Display Instructions


AECL
Part of Master of Science Thesis
by
C.E. Linskens

AECL

The Rationale of the Newly Proposed ECL



- The Design aims at lowering the workload as much as possible and stimulate the pilot to perform the decision making and consequential thinking
- Workload is lowered by relieving the pilot from manually executing the checklist steps through automation
- Workload is further lowered by presenting pilots only with mission or system impacting information, or where pilot input may be required
- This enforces fast completion of the checklists and focusses attention on important information only. This aims to stimulate efficient use of cognitive resources
- Where needed, pilots have the option to access the complete checklist to obtain further context

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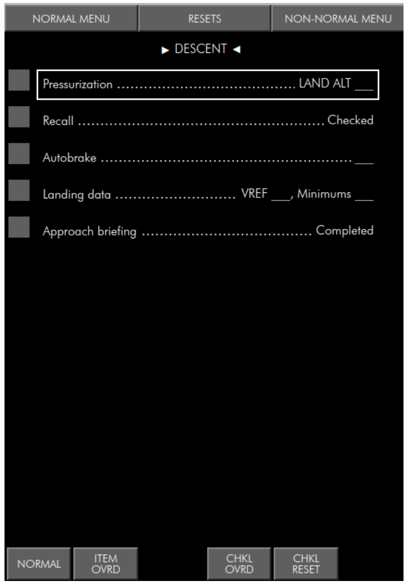
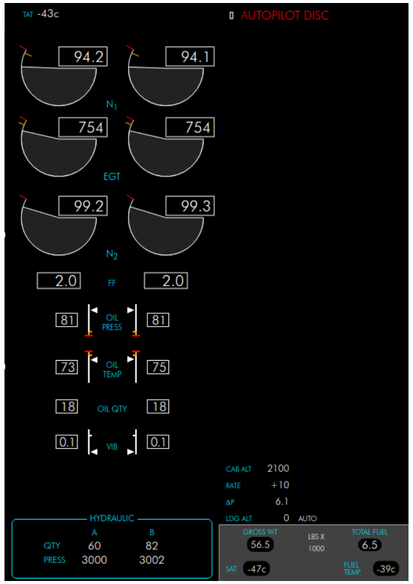
Automating a Checklist

Flying Safely ...



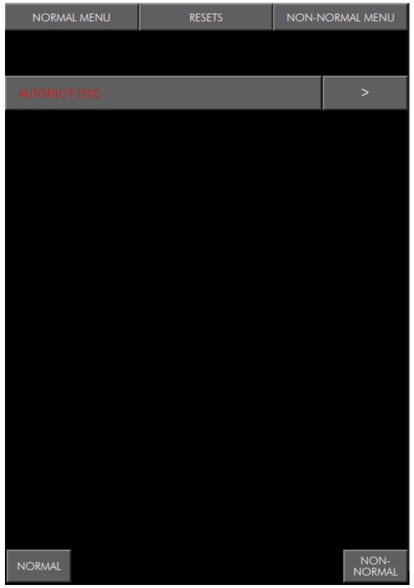
- No failures are present right now
- On the ECL display the next Normal checklist is shown
- In this case the Descent checklist since the aircraft is in cruise

First EICAS message appears



- Autopilot disconnect message is shown on EICAS
- In front of AUTOPILOT DISC a white box is present indicating an incomplete checklist is available for the respective message

On the ECL display



- The ECL display shows the AUTOPILOT DISC checklist

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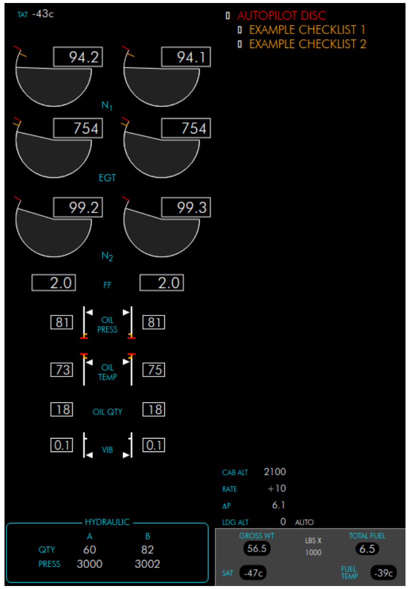
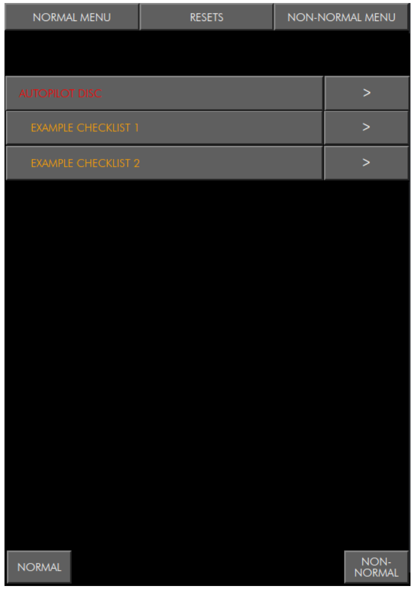
Automating a Checklist (Cont'd)

Some more failures …



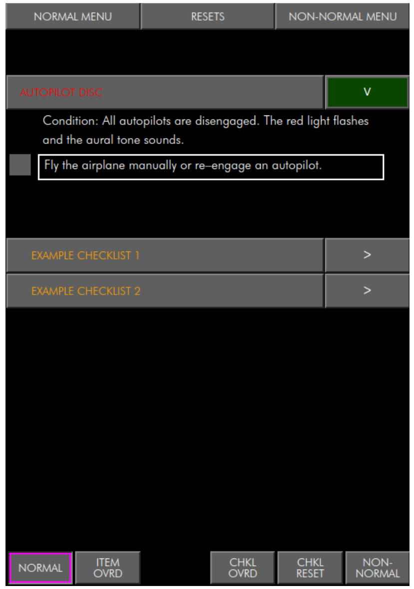
- EICAS now shows messages with associated checklists for EXAMPLE CHECKLIST 1 and EXAMPLE CHECKLIST 2

… And the ECL is updated



- Now three messages are shown on the ECL

Opening a checklist



- Checklist can be opened by pressing on the right-side button
- A dropdown menu shows

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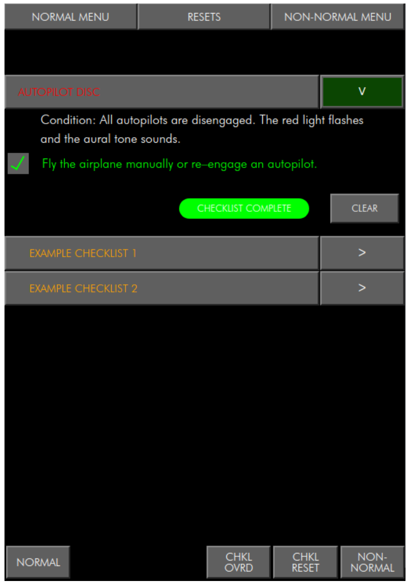
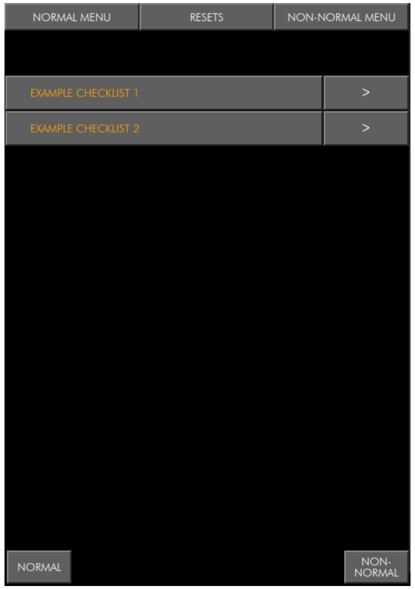
Automating a Checklist (Cont'd)

Some more failures …



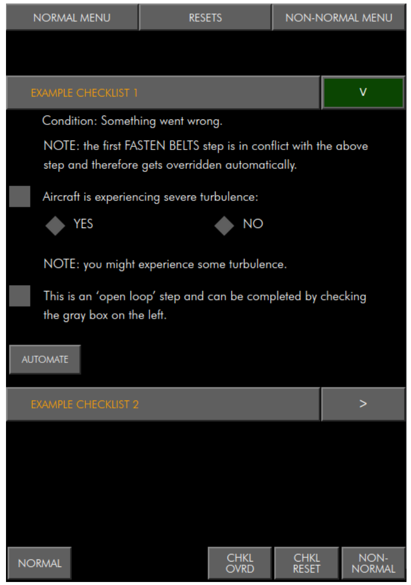
- Checklist is now completed
- And the CLEAR button can be pressed

… And the ECL is updated



- The AUTOPILOT DISC checklist is now removed from the ECL

Opening CHECKLIST 1



- Opening checklist 1 shows the condition, notes and the steps to be completed by you
- Also an AUTOMATE button is shown since this checklist has steps which can be automated

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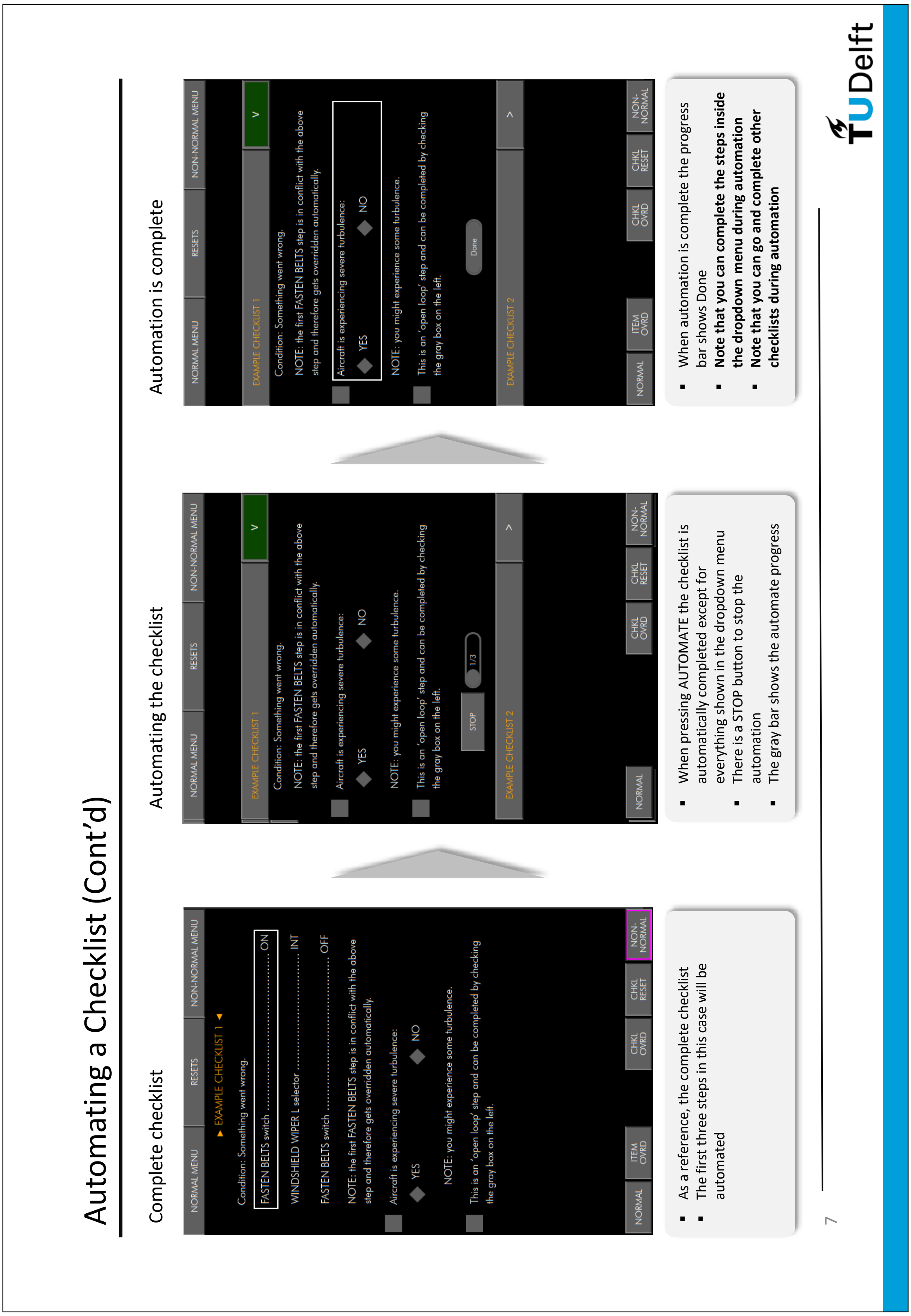
Automating a Checklist (Cont'd)
Complete checklist
NORMAL MENU
RESETS
NON-NORMAL MENU
EXAMPLE CHECKLIST 1
Condition: Something went wrong.
FASTEN BELTS switch .... ON
WINDSHIELD WIPER L selector .... INT
FASTEN BELTS switch .... OFF
NOTE: the first FASTEN BELTS step is in conflict with the above step and therefore gets overridden automatically.
Aircraft is experiencing severe turbulence:
YES
NO
NOTE: you might experience some turbulence.
This is an 'open loop' step and can be completed by checking the gray box on the left.
NORMAL
ITEM OVRD
CHKL OVRD
CHKL RESET
NON-NORMAL
As a reference, the complete checklist
The first three steps in this case will be automated
Automating the checklist
EXAMPLE CHECKLIST 1
STOP
1/3
EXAMPLE CHECKLIST 2
When pressing AUTOMATE the checklist is automatically completed except for everything shown in the dropdown menu
There is a STOP button to stop the automation
The gray bar shows the automate progress
Automation is complete
Done
When automation is complete the progress bar shows Done
Note that you can complete the steps inside the dropdown menu during automation
Note that you can go and complete other checklists during automation
7
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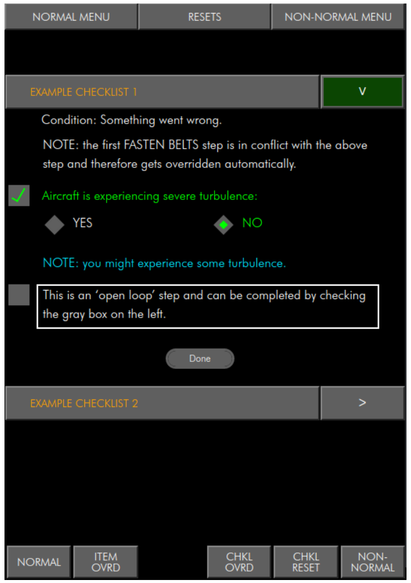
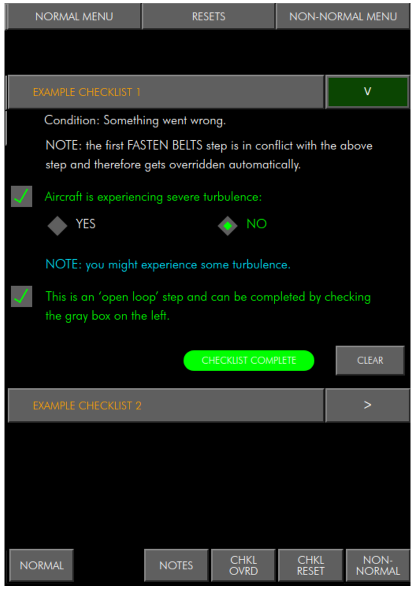
Automating a Checklist (Cont'd)

Completing steps in dropdown menu



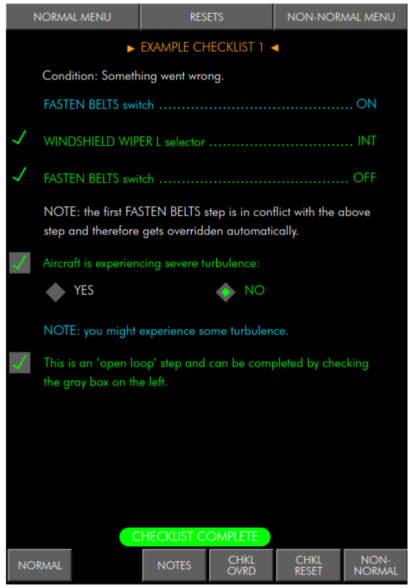
- Completing the choose step

Completing steps in dropdown menu (cont'd)



- Completing the Open loop step
- Checklist is now complete and can be cleared by pressing the CLEAR button

What happened inside the checklist?



- Above is an overview of the result of combining automation and completing the steps from the dropdown menu

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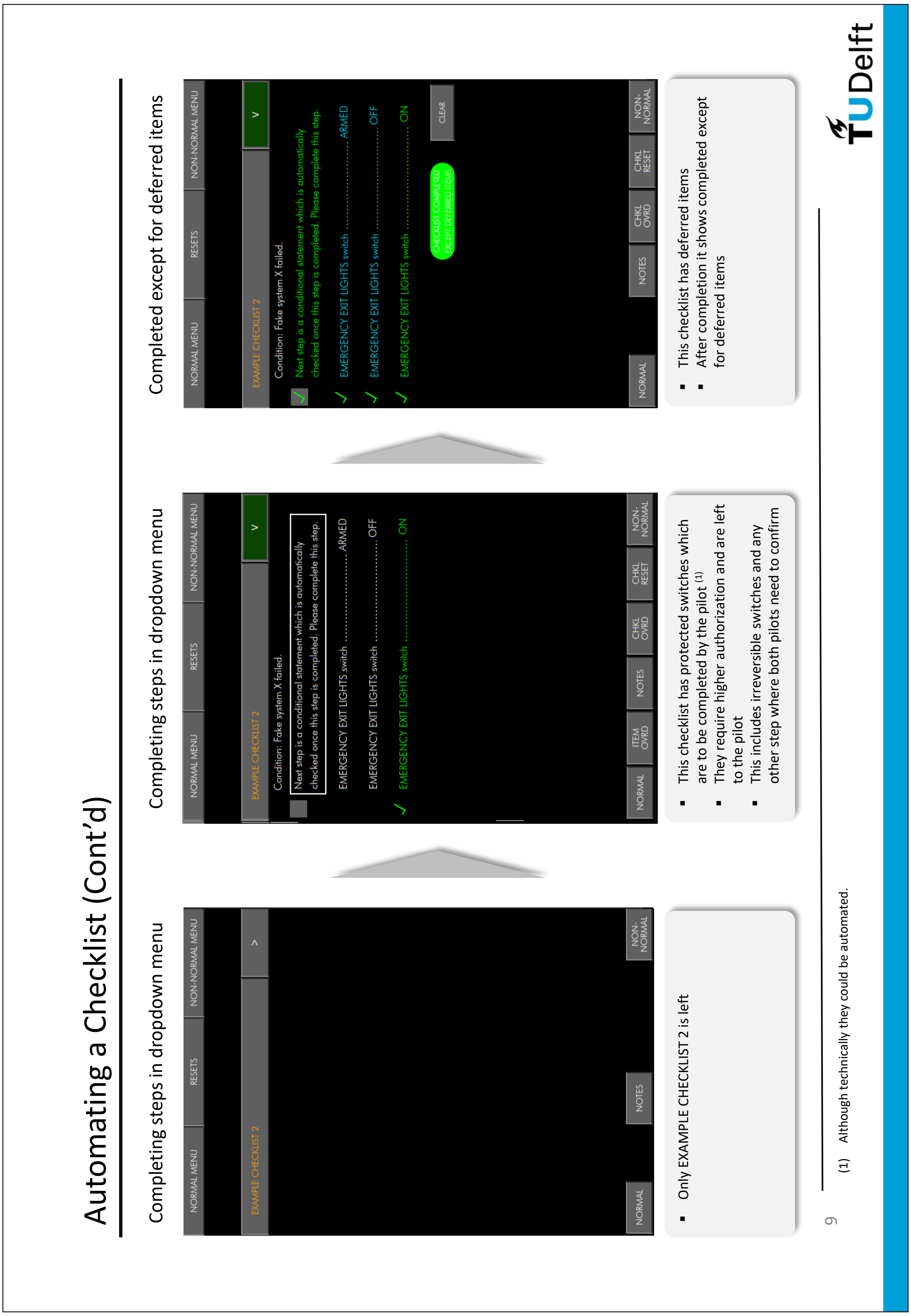
Automating a Checklist (Cont'd)
Completing steps in dropdown menu
NORMAL MENU
RESETS
NON-NORMAL MENU
EXAMPLE CHECKLIST 2
NORMAL
NOTES
NON-NORMAL
Only EXAMPLE CHECKLIST 2 is left
Completing steps in dropdown menu
EXAMPLE CHECKLIST 2
Condition: Fake system X failed.
Next step is a conditional statement which is automatically checked once this step is completed. Please complete this step.
EMERGENCY EXIT LIGHTS switch .... ARMED
EMERGENCY EXIT LIGHTS switch .... OFF
EMERGENCY EXIT LIGHTS switch .... ON
ITEM OVRD
CHKL OVRD
CHKL RESET
This checklist has protected switches which are to be completed by the pilot (1)
They require higher authorization and are left to the pilot
This includes irreversible switches and any other step where both pilots need to confirm
Completed except for deferred items
CHECKLIST COMPLETED EXCEPT DEFERRED ITEMS
CLEAR
This checklist has deferred items
After completion it shows completed except for deferred items
(1) Although technically they could be automated.
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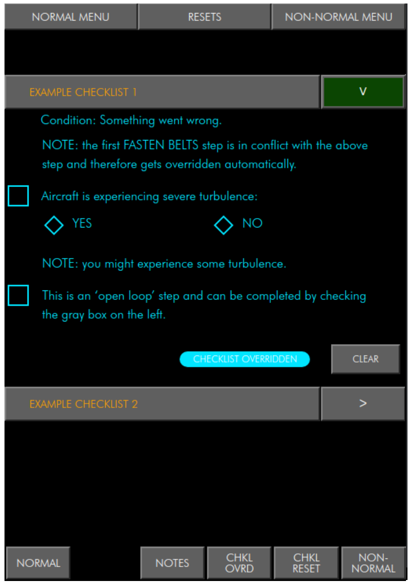
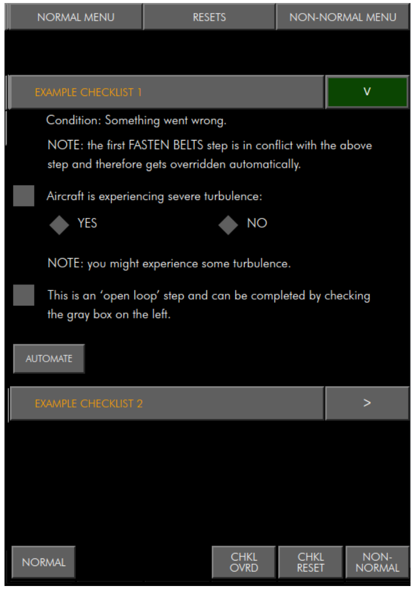
Automating a Checklist (Cont'd)

Checklist override



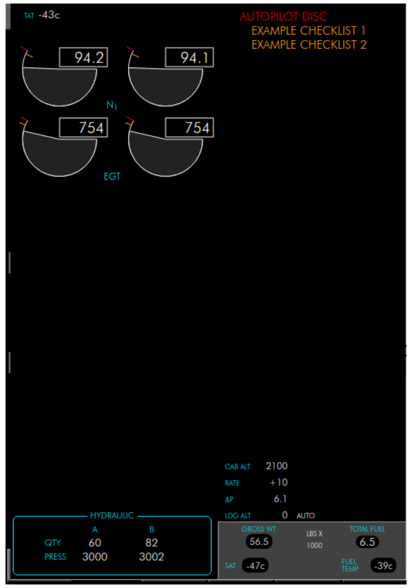
- Checklist can be overridden
- Result is that everything becomes blue and the checklist can be removed

Opening a checklist



- When opening a checklist all others are closed
- This is done to keep the ECL orderly

Everything is completed



- When all checklists are completed all white boxes in front of the EICAS messages are gone
- Also the ECL will jump to the next Normal checklist, in this case the Descent checklist

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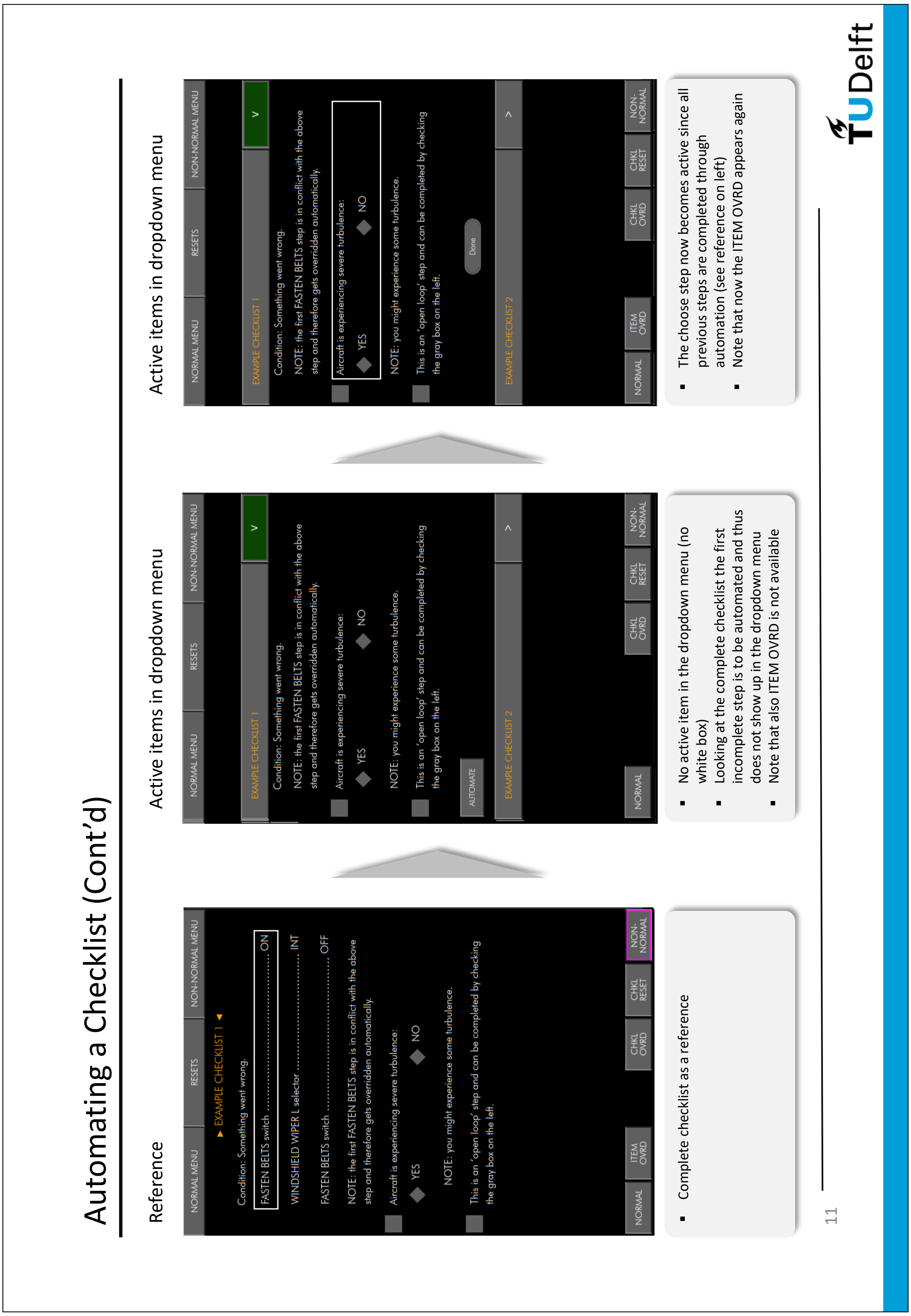
Automating a Checklist (Cont'd)
Reference
NORMAL MENU
RESETS
NON-NORMAL MENU
▸ EXAMPLE CHECKLIST 1 ◂
Condition: Something went wrong.
FASTEN BELTS switch .... ON
WINDSHIELD WIPER L selector .... INT
FASTEN BELTS switch .... OFF
NOTE: the first FASTEN BELTS step is in conflict with the above step and therefore gets overridden automatically.
Aircraft is experiencing severe turbulence:
YES
NO
NOTE: you might experience some turbulence.
This is an 'open loop' step and can be completed by checking the gray box on the left.
NORMAL
ITEM OVRD
CHKL OVRD
CHKL RESET
NON-NORMAL
Complete checklist as a reference
Active items in dropdown menu
EXAMPLE CHECKLIST 1
EXAMPLE CHECKLIST 2
AUTOMATE
No active item in the dropdown menu (no white box)
Looking at the complete checklist the first incomplete step is to be automated and thus does not show up in the dropdown menu
Note that also ITEM OVRD is not available
Active items in dropdown menu
Done
The choose step now becomes active since all previous steps are completed through automation (see reference on left)
Note that now the ITEM OVRD appears again
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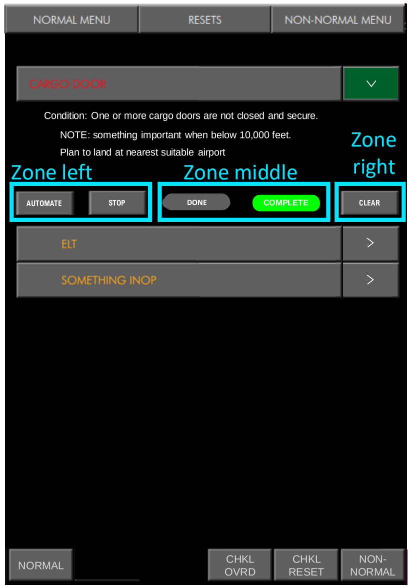
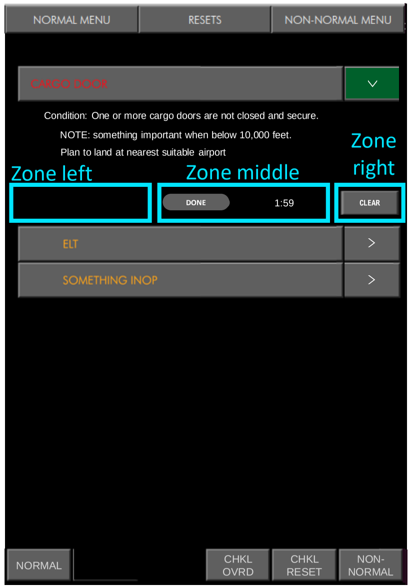
The Three Zones





- Zone on left allows pilot to handle automation, by either automating or stopping automation
- Middle zone shows progress status of the checklist; the automated part and the complete checklist. Also a timer can show up for steps which require longer to complete
- Standard time required to move switches is 0.5 seconds
- On the right, the pilot can clear a checklist
- Note that the zones show *all* buttons available (some are thus not present concurrently)

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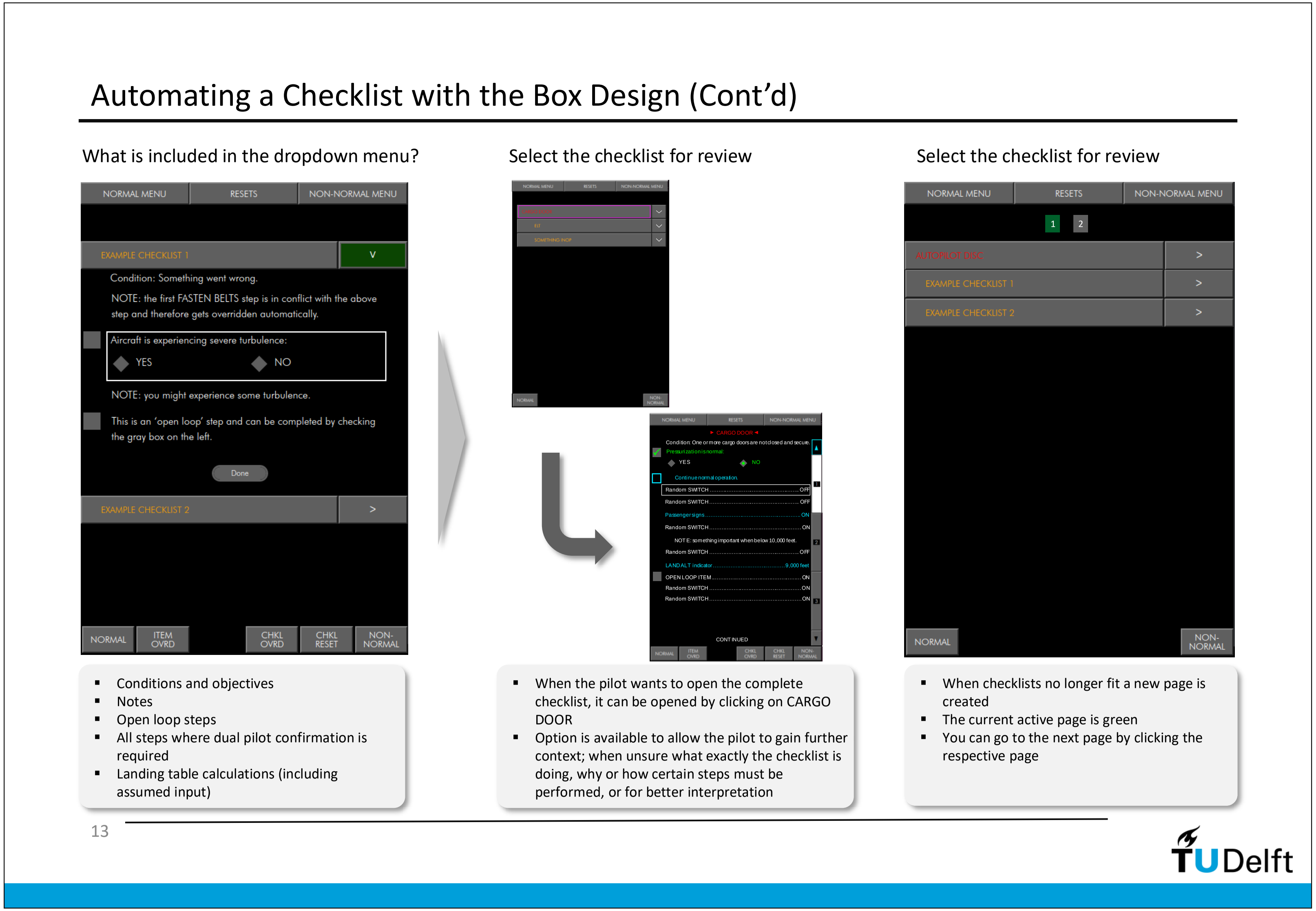
Automating a Checklist with the Box Design (Cont'd)
What is included in the dropdown menu?
NORMAL MENU
RESETS
NON-NORMAL MENU
EXAMPLE CHECKLIST 1
V
Condition: Something went wrong.
NOTE: the first FASTEN BELTS step is in conflict with the above step and therefore gets overridden automatically.
Aircraft is experiencing severe turbulence:
YES
NO
NOTE: you might experience some turbulence.
This is an 'open loop' step and can be completed by checking the gray box on the left.
Done
EXAMPLE CHECKLIST 2
>
NORMAL
ITEM OVRD
CHKL OVRD
CHKL RESET
NON-NORMAL
Conditions and objectives
Notes
Open loop steps
All steps where dual pilot confirmation is required
Landing table calculations (including assumed input)
Select the checklist for review
When the pilot wants to open the complete checklist, it can be opened by clicking on CARGO DOOR
Option is available to allow the pilot to gain further context; when unsure what exactly the checklist is doing, why or how certain steps must be performed, or for better interpretation
Select the checklist for review
NORMAL MENU
RESETS
NON-NORMAL MENU
1
2
AUTOPILOT DISC
EXAMPLE CHECKLIST 1
EXAMPLE CHECKLIST 2
NORMAL
NON-NORMAL
When checklists no longer fit a new page is created
The current active page is green
You can go to the next page by clicking the respective page
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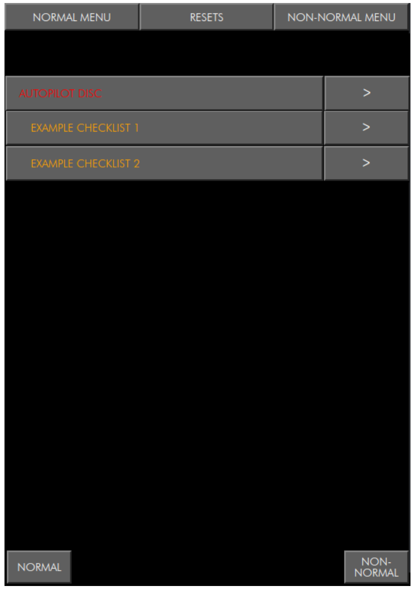
How to Operate?



- You may access the checklist beforehand to verify what is included
- However, during automation we would like you to not access the checklist to force you to work in a manner as per the design
- It can be assumed this is the new standard operating procedure
- Note that you are however free to access the checklist once automation is completed

TUDelft

L
Experiment Checklist

Checklist - Experiment

Part of Master of Science Thesis

by

C.E. Linskens

TU Delft

Checklist   Participant: Date:

Before Training:

- [ ] Clean hands
- [ ] Briefing
- [ ] Discuss Flight Plan
- [ ] Discuss QRH and Landing Configuration Tables
- [ ] Walk through EICAS
- [ ] Walk through ECL
- [ ] Complete Consent Form
- [ ] Complete Introduction Survey
- [ ] Explain manipulation of touch cockpit
- [ ] Mention the same Flight Plan is used and the same initial configuration is used
- [ ] Set seat in forward position

Before Measurements:

- [ ] Complete training scenario
- [ ] Complete training survey
- [ ] Participant is comfortable with the ECL and the cockpit

Completing Measurements:

- [ ] Complete scenario 1
- [ ] Complete survey 1
- [ ] Complete scenario 2
- [ ] Complete survey 2
- [ ] Complete post experiment survey

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M

Post Scenario and Post Experiment Open Questions

Post scenario and post experiment various open questions were required to be filled out by the participant. Participants made use of a dedicated keyboard and mouse to fill out the question, which were stored on Qualtrics.

M.1. Post Scenario

Please describe to the best of your knowledge what underlying failure(s) you experienced.

Please describe the decision process of choosing your airport of destination.
Please indicate what factors contributed to making your decision?

Please describe any other factors you considered which hypothetically could have driven your decision for a landing airport? (For example, if it was raining I wouldn't land at this airport since system X is inoperative)

M.2. Post Experiment

What operational challenges do you see using the ECL?

To improve the ECL, what features can be added?

How did you experience i) the 'touch' manipulation on the ECL and ii) the the 'touch' manipulation of the cockpit (overhead, etc.)?

How did you utilise the ECL during the scenarios?

Please describe your strategy step by step. Consider topics such as:

- How did you prioritize checklists?
- To what extend and why did you analyze checklists beforehand (before starting its completion)?
- Did you complete multiple checklists concurrently or one by one?

Example: i) message arrives through EICAS, ii) I check which checklists show up on the ECL to plan my next steps, iii) etc.

Would you like to see the ECL integrated in your aircraft?

M.3. Post Experiment AECL (additional)

Were you comfortable with automating the checklist? If not, why?

How did you experience the dropdown menu of the ECL?

How did you experience pressing the CLEAR button? Or would you rather see an automatic removal of the checklist? Why?

Did you require to analyze the complete checklist beforehand or were you confident with the feedback presented by the ECL in the menu? If not, what would you like to see changed?

Were you confident with not missing any information when using automation?

N

Post Scenario and Post Experiment Open Question Answers

This appendix outlines every participant's answers to the open questions after each scenario and after the experiment. Participants were able to fill out the questions by utilising a keyboard and mouse. Finally, all entries are raw data as submitted by the participant.

N.1. Post Scenario

N.1.1. Drive Shaft Failure

Participant 1 (ECL)

1. Please describe to the best of your knowledge what underlying failure(s) you experienced.

gen fail, window heat fail, antiskid fail.

2. Please describe the decision process of choosing your airport of destination.

Checklist states land at nearest suitable airport. Engine failure eng 2 could result in batt only power.

3. 3. Please describe any other factors you considered which hypothetically could have driven your decision for a landing airport? (For example, if it was raining I wouldn't land at this airport since system X is inoperative)

None

Participant 2 (ECL)

1. Please describe to the best of your knowledge what underlying failure(s) you experienced.

Transfer Bus 1 failed. This type of Failure can be recognised by several system failures, as can been seen on the overhead panel. Some can usually be reset, some can't.

2. Please describe the decision process of choosing your airport of destination.

Checklist indicates Land at Nearest Airport. I then have a look at this airport with regard to WX and Approach/Runway availability. Also the failure resulated in loss of Antiskid which directly influences the landing distance required. I also take this information in my decision making with regard to the diversion airport.

3. Please describe any other factors you considered which hypothetically could have driven your decision for a landing airport? (For example, if it was raining I wouldn't land at this airport since system X is inoperative)

X-wind restriction with Flaps 30, Non-Normal Landing Distance table for Anti-skid speaks about Flaps 40. With a lot of x-wind I might have chosen a different runway/airport. If it was raining Landing Distance required would have been much more. This could have resulated in choosing a different airport for diversion.

Participant 3 (ECL)

1. Please describe to the best of your knowledge what underlying failure(s) you experienced.

Failure of IDG1 and a BTB (bus tie breaker), with associated consequential failures.

2. Please describe the decision process of choosing your airport of destination.

As weather is good and no marginal conditions are present, decision to divert to the airfield which is closest (timewhise) is easily made. Shoudl for instance your intended destination be at 5mins more flighttime, consideration at least would have been given to maybe continue to destination. Difference in time in this scenario is larger.

3. Please describe any other factors you considered which hypothetically could have driven your decision for a landing airport? (For example, if it was raining I wouldn't land at this airport since system X is inoperative)

Prevailing weather both enroute and at intended lannding field; 'nearest' as seen from a time point-of-view: should the 'closest' airport be into 100kts HW wherea the destination would be more distant but closer 'in time', this would be preferable.

Participant 4 (ECL)

1. Please describe to the best of your knowledge what underlying failure(s) you experienced.

Gen drive failure 1, leading to source off and gen off buss lights

Probably also some underlying electrical bus or relay failure leading to seemingly unrelated Fuel Pump Left FWD, Right AFT, Autopilot A, Hydraulic ELEC 1 and window heat failures, as these are also on buses on the same side.

2. Please describe the decision process of choosing your airport of destination.

With one generator still on line and normal hydarulic and fuel pressure, there was no immediate need to land. We were limited to Flaps 30 if the crosswind would exceed 30 kts, and we had no Autobrake. The weather indicated that light winds were to be expected at USTR, no rain. So a dry runway, of plenty length (gt;3000m available, approx. 1575m required). So a landing at USTR was perfectly feasible. Furthermore, USTR would have handling for the pax.

We were also limited to non-icing conditions due to the probe heat fail, but weather was clear along the route, so no problem.

A switched off IDG does require maintenance, so in real life, I would have contacted the company to discuss whether to continue or return to UAUU.

3. Please describe any other factors you considered which hypothetically could have driven your decision for a landing airport? (For example, if it was raining I wouldn't land at this airport since system X is inoperative)

See previous answer. If the weather at USTR was such that the runway would become limiting (crosswind, breaking action), we would have needed to divert.

Also if enroute icing conditions were to be expected, or icing conditions at USTR, a diversion might have been appropriate.

So it boils down to the maintenace facilities at USTR. If hey cannot repair the IDG, we will be stuck there.

Participant 5 (ECL)

1. Please describe to the best of your knowledge what underlying failure(s) you experienced.

Autopilot A disconnected but got reengaged with Autopilot B There was a Generator 1 failure. Which led to some system 1 connected failures.

2. Please describe the decision process of choosing your airport of destination.

We were flying towards BEBLU (220NM out) and parallel of BEBLU lays UAUU (alternate). Because of the connected generator 1 system failures we decided 150NM out of BEBLU to divert to UAUU. Because of the window heat and possible icing conditions at USTR.

3. Please describe any other factors you considered which hypothetically could have driven your decision for a landing airport? (For example, if it was raining I wouldn't land at this airport since system X is inoperative)

Possible mist (MIFG BR) at USTR. NNC reported to land at the nearest possible airport due to the loss of a generator. UAUU therefor was the best option.

Participant 6 (ECL)

1. Please describe to the best of your knowledge what underlying failure(s) you experienced.

various multiple failures gen. fuel.hyd.wnd heat

2. Please describe the decision process of choosing your airport of destination.

according v list

3. Please describe any other factors you considered which hypothetically could have driven your decision for a landing airport? (For example, if it was raining I wouldn't land at this airport since system X is inoperative)

none

Participant 7 (AECL)

1. Please describe to the best of your knowledge what underlying failure(s) you experienced.

transfer bus failure left multiple related electrical components shut down because of transfer bus dependance

2. Please describe the decision process of choosing your airport of destination.

destination en alternate ongeveer even ver en ik had toch nog tijd nodig om alle checklisten nog te completeren. uitwijk gaat in 'terms of time' [TRANSLATED] Destination and alternate approximately equally far and I had plenty of time to complete all checklists. Divertion is a 'time matter'

3. Please describe any other factors you considered which hypothetically could have driven your decision for a landing airport? (For example, if it was raining I wouldn't land at this airport since system X is inoperative)

het weer gaf geen icing conditions aan dus we hoefden geen keuze te maken vanwege icing conditions omdat er enkele delen van het anti ice systeem niet meer functioneerden according chklist [TRANSLATED] The weather did not indicate icing condition and thus no choice had to be made in respect of icing conditions because some parts of the anti-icing system did no longer function according to the checklist(s)

Participant 8 (AECL)

1. Please describe to the best of your knowledge what underlying failure(s) you experienced.

Loss of hyd syst, AP, window heat, fuel pumps, AC gen

2. Please describe the decision process of choosing your airport of destination.

Checklists stated divert to nearest suitable airport

3. Please describe any other factors you considered which hypothetically could have driven your decision for a landing airport? (For example, if it was raining I wouldn't land at this airport since system X is inoperative)

WXR, available RWY, available approaches

Participant 9 (AECL)

1. Please describe to the best of your knowledge what underlying failure(s) you experienced.

Generator One seemed to be failed, therefore various system lights illuminated. Because APU is unserviceable nog other main AC power source could be activated and only only one main ac power source remained.

2. Please describe the decision process of choosing your airport of destination.

Checklist stated to land at nearest suitable airport. Objectively this would have been the alternate airport, but because difference in distance was not very large decision was made to continue to destination airport. Both airports seemed to be suitable for landing and commercial drive gives preference to destination airport.

3. Please describe any other factors you considered which hypothetically could have driven your decision for a landing airport? (For example, if it was raining I wouldn't land at this airport since system X is inoperative)

Icing conditions
Turbulence conditions
Runway length

Participant 10 (AECL)

1. Please describe to the best of your knowledge what underlying failure(s) you experienced.

A Main Bus failure or drive issue disengages a lot of other systems. Some of them irreversibly some of them can be reengaged. It is a lot of checklist the pilot has to do. But most of the failed systems are not directly a major problem.

2. Please describe the decision process of choosing your airport of destination.

APU was inop so no backup power available after disconnecting the GEN 1 Drive. I decided to divert because there was no backup power (except of the battery) available. Weather (icing conditions or not) can be a reason to change the path.

3. Please describe any other factors you considered which hypothetically could have driven your decision for a landing airport? (For example, if it was raining I wouldn't land at this airport since system X is inoperative)

-

Participant 11 (AECL)

1. Please describe to the best of your knowledge what underlying failure(s) you experienced.

Left generator failure, causing some more systems to fail. including antiskid

2. Please describe the decision process of choosing your airport of destination.

Decided to divert to alternate, which was closer then my destination. plan to land at the nearest suitable airport. contributing factors weather and runway lenght

3. Please describe any other factors you considered which hypothetically could have driven your decision for a landing airport? (For example, if it was raining I wouldn't land at this airport since system X is inoperative)

bad weather because now we're down to one autopilot or a short runway because landing distance increases with antiskid inop.d

Participant 12 (AECL)

1. Please describe to the best of your knowledge what underlying failure(s) you experienced.

It seemed like a generator failure. An electrical failure affects many subsystems, therefore a large amount of checklists/failures appeared.
The following systems where affected: fuel system (pumps), hydraulic system (elec pump), flight controls (yaw damper), anti-ice (window heat, probe heat, ...), automation (A/P A), landing gear (nose wheel steering, braking)

2. Please describe the decision process of choosing your airport of destination.

The checklist instructed to land at the nearest suitable airport. That was the main driver for choosing to divert to the alternate airport.

3. Please describe any other factors you considered which hypothetically could have driven your decision for a landing airport? (For example, if it was raining I wouldn't land at this airport since system X is inoperative)

There were no other factors to consider. Weather and facilities were sufficient at both destination and alternate airport.

N.1.2. Hydrualic Leak Failure

Participant 1 (ECL)

1. Please describe to the best of your knowledge what underlying failure(s) you experienced.

hyd failure

2. Please describe the decision process of choosing your airport of destination.

Manual gear extension, dest altnt is nearby, able to arrive at an airport with more fuel in case of missed approach and flt control problems, better equipment for approaches (ILS), headwind for landing.

3. Please describe any other factors you considered which hypothetically could have driven your decision for a landing airport? (For example, if it was raining I wouldn't land at this airport since system X is inoperative)

Possible missed approach, possible flt control problems.

Participant 2 (ECL)

1. Please describe to the best of your knowledge what underlying failure(s) you experienced.

Autopilot A disconnect, most likely caused by a drop in Hydraulic Qty system 1. Drop in Qty and Pressure in Hyd. 1 was noticed prior A/P disconnect and prior to Master Caution/Warning pop-up. Loss of Hydraulic Sys. 1 resulated in amongst other Manual Gear Extension.

2. Please describe the decision process of choosing your airport of destination.

Closer to Destination than Departure aerodrome. WX and runway length at Destination were good/enough for the failure. I presume Destination is a regular Destination for us, and thus handling and possible technical assistance on the ground are sufficient. Lastly, commercially good to be able to land and destination.

3. Please describe any other factors you considered which hypothetically could have driven your decision for a landing airport? (For example, if it was raining I wouldn't land at this airport since system X is inoperative)

WX and thus likelyhood of making a succesful landing, multiple runways. Since Manual Gear extension is irreversible Fuel Flow would be much higher in case of a Go Around and possible diversion to an Alternate. There is a high chance that diversion after a Go Around is not possible anymore (due Gear Down and high Fuel Flow).

Participant 3 (ECL)

1. Please describe to the best of your knowledge what underlying failure(s) you experienced.

Decrease of HYD A qty, resulting in LOW PRESS and O/HEAT. As a consequence, loss of AP A, some FLT CTL's and later on MANUAL GEAR EXT. (operational consequences not mentioned here).

2. Please describe the decision process of choosing your airport of destination.

Availability of HYD B and STDBY HYD. Good handling performance and good fuel state of the aircraft upon arrival. Sufficient weather and variables to continue to DEST, no need at this time to divert enroute. Availability of tech assistance upon arrival and consequences for pax. Options in case of deterioration of the situation (LOSS of HYD A and B).

3. Please describe any other factors you considered which hypothetically could have driven your decision for a landing airport? (For example, if it was raining I wouldn't land at this airport since system X is inoperative)

If weather would have been marginal in case of further system deterioration. Low fuel state in case of such weather. Marginal operating conditions (e.g. marginal RWY length,...). Logistical considerations (handling etc)... After tackling the situation at hand first, consequences were evaluated (incl. deterioration an dalternatives) to support the decision.

Participant 4 (ECL)

1. Please describe to the best of your knowledge what underlying failure(s) you experienced.

Hydraulic leak system A, leading to loss of pressure of Hydr sys A, leading to loss of associated systems (flt controls A, Landing gear ext/retr, normal nose wheel stearing)

2. Please describe the decision process of choosing your airport of destination.

Loss of redundancy, but no immediate threat. Landing distance at destination more than adequate. Main concern is availability of maintenance at USTR.

3. Please describe any other factors you considered which hypothetically could have driven your decision for a landing airport? (For example, if it was raining I wouldn't land at this airport since system X is inoperative)

Due to the inability to retract the gear, a diversion is not possible after gear extension. So you need to be fairly certain that the conditions at your destination allow you to land, weather, wind, runway length. This was the case in this scenario. Secondly, maintenance is required to fix the leak, so you want to land somewhere where they can fix the plane.

Participant 5 (ECL)

1. Please describe to the best of your knowledge what underlying failure(s) you experienced.

1) Autopilot A disconnected. 2) Hydraulic Sys A failure with a overheated ELEC pump.

2. Please describe the decision process of choosing your airport of destination.

Once the NNC for both failures were completed we had 6700kg of fuel left and roughly 40min away from USTR. Due to the Autopilot A failure we had to decent to FL280 due to unable RVSM requirements so that would increase the fuel consumption. But with the fuel onboard, increased landing distance I would have chosen RWY 15L at USTR due to an operative ILS system and long runway length.

3. Please describe any other factors you considered which hypothetically could have driven your decision for a landing airport? (For example, if it was raining I wouldn't land at this airport since system X is inoperative)

- Landing system available + weather - Fuel (lower altitude due to not RVSM capable) - Runway length

Participant 6 (ECL)

1. Please describe to the best of your knowledge what underlying failure(s) you experienced.

hydr. failure man. gear extension

2. Please describe the decision process of choosing your airport of destination.

all according to v list again, relaying on info v list

3. Please describe any other factors you considered which hypothetically could have driven your decision for a landing airport? (For example, if it was raining I wouldn't land at this airport since system X is inoperative)

cannot complete v list as we were not yet landing

Participant 7 (AECL)

1. Please describe to the best of your knowledge what underlying failure(s) you experienced.

hyd sys a failure

2. Please describe the decision process of choosing your airport of destination.

manual gear extension needs timely gear down. extra fuel needed to have enough for a go around also so not enough fuel at destination, alternate was a little closer

3. Please describe any other factors you considered which hypothetically could have driven your decision for a landing airport? (For example, if it was raining I wouldn't land at this airport since system X is inoperative)

n/a

Participant 8 (AECL)

1. Please describe to the best of your knowledge what underlying failure(s) you experienced.

Loss of syst A hydraulic

2. Please describe the decision process of choosing your airport of destination.

the state of the aircraft

3. Please describe any other factors you considered which hypothetically could have driven your decision for a landing airport? (For example, if it was raining I wouldn't land at this airport since system X is inoperative)

n/a

Participant 9 (AECL)

1. Please describe to the best of your knowledge what underlying failure(s) you experienced.

Hyd sys A has failed during flight. Probable cause might be a system leak. Hydraulic quantities indicated 0 and all low pressure lights illuminated.

2. Please describe the decision process of choosing your airport of destination.

Destiantion airport as planned has a suitable runway in terms of length and approach aids. Also, the checklist did not dictate any specific types of approaches which could not be used so no reason to divert to alternate airport.

3. Please describe any other factors you considered which hypothetically could have driven your decision for a landing airport? (For example, if it was raining I wouldn't land at this airport since system X is inoperative)

If weather conditions would have been such that a dual autopilot landings must have been made, this would have been impossible because of the failre.

Participant 10 (AECL)

1. Please describe to the best of your knowledge what underlying failure(s) you experienced.

HYD A failure (no pressure) means that you loose some of your redundancy by using the alternate systems like alternate nose wheel steering and manual gear extension and longer landing distance. This is more a replanning thing.

2. Please describe the decision process of choosing your airport of destination.

Available runway length and weather, in real life also maintenance/assistance. Can I still land with the changed conditions. Everything was good to continue for a landing.

3. Please describe any other factors you considered which hypothetically could have driven your decision for a landing airport? (For example, if it was raining I wouldn't land at this airport since system X is inoperative)

Increased drag could make it impossible to reach my alternate, but multiple runways are available. If I still had to divert I couldn't retract the gear.

Participant 11 (AECL)

1. Please describe to the best of your knowledge what underlying failure(s) you experienced.

Loss of hydraulic system A

2. Please describe the decision process of choosing your airport of destination.

runway lenght, approach procdure and weather made me choose to continue to destination.

3. Please describe any other factors you considered which hypothetically could have driven your decision for a landing airport? (For example, if it was raining I wouldn't land at this airport since system X is inoperative)

short or contaminated runway, good weather conditions since we have have to commit landing at the airport, because once you do the manual gear extension the gear doesn't retract.

Participant 12 (AECL)

1. Please describe to the best of your knowledge what underlying failure(s) you experienced.

Hydraulic System A failure (qty and press decreased to zero) resulting in different other failure; e.g. Autopilot disc and failure of A/P A.

2. Please describe the decision process of choosing your airport of destination.

Due to the failure requiring alternate gear extension and possible extra time needed to configure and get ready for an approach the alternate airport buys some time that might be needed. An early configuration, and also flying longer with extended gear, will cost more fuel. An early decision to divert to the alternate results in extra fuel on board which might be needed when flying in a high drag configuration.

3. Please describe any other factors you considered which hypothetically could have driven your decision for a landing airport? (For example, if it was raining I wouldn't land at this airport since system X is inoperative)

As the weather is good enough the fact that the alternate airport only has an RNAV approach is not a reason not to go there. If the weather would have been worse I would have considered going to the destination as there are more options in possible runways. As it is unknown what caused the hydraulic failure, flying longer than necessary is not desired.

N.2. Post Experiment

Participant 1 (ECL)

1. What operational challenges do you see using the ECL?

Lack of overview because of lack of knowledge or use of human to hardware communication. No use of colors in the ECL menu, not clear in what menu the user is working, no overview during working in different menu's etc. Overall thought is that the designers where still thinking in an conventional matter, while designing an ECL based on a futuristic and innovative philosophy.

2. To improve the ECL, what features can be added?

Use colors, always show a header about the subject, always give an summary window of all checklists when working in a particular checklist. Let the user be able to work in a sequence matter, so when a checklist has been completed to be able to press a next checklist button i.s.o letting the user go back to the initial menu again and again...

3. How did you experience i) the 'touch' manipulation on the ECL and ii) the the 'touch' manipulation of the cockpit (overhead, etc.)?

Good

4. How did you utilise the ECL during the scenarios?

First have an overview, then decide. After completing all checklists make a decision.

5. Please describe your strategy step by step. Consider topics such as:

- How did you prioritize checklists?
- To what extend and why did you analyze checklists beforehand (before starting its completion)?
- Did you complete multiple checklists concurrently or one by one?

Example: i) message arrives through EICAS, ii) I check which checklists show up on the ECL to plan my next steps, iii) etc.

I do not think it improved my SA. It made it worse perhaps.

6. Would you like to see the ECL integrated in your aircraft?

Not this one please.

Participant 2 (ECL)

1. What operational challenges do you see using the ECL?

With a physical checklist you can physically put the checklist away to focus on other things, or e.g. hand over the checklist to colleague to double check.
ECL generates more 'head-down' for Pilot.

2. To improve the ECL, what features can be added?

The 'blue' items are sometimes a bit confusing. I am being direct to do some system switching on the Overhead Panel. After looking down almost the whole checklist is completed, including some blue items which still show boxes.
I'm tempted to try to push these boxes and I still feel I need to go through all the steps, in order for me to feel that the checklist is really completed.

3. How did you experience i) the 'touch' manipulation on the ECL and ii) the the 'touch' manipulation of the cockpit (overhead, etc.)?

Touch manipulation is ok. Especially with regard to the ECL. With regard to the actual switching on the Overhead Panel, it's something I would have to get used to. All switches are physically different from eachother. You don't feel this difference in the current way of a touch-panel.

4. How did you utilise the ECL during the scenarios?

Looking at Master Warning (red) checklists first, from top to bottom. I usually look over the checklist, to see of current steps will required e.g. a certain speed or altitude or perhaps time. This I take into account for planning purposes.
I jumped to a different checklist, halfway one checklist. Because that checklist indicated a waiting period of 2 minutes. Plus I wanted to know what info the next checklist would give me, because this might have changed my decision making with regard to the Diversion Airport.

5. Please describe your strategy step by step. Consider topics such as:

- How did you prioritize checklists?
- To what extend and why did you analyze checklists beforehand (before starting its completion)?
- Did you complete multiple checklists concurrently or one by one?

Example: i) message arrives through EICAS, ii) I check which checklists show up on the ECL to plan my next steps, iii) etc.

You can see where you left of, after being distracted. So that part helps. The fact that many items are checked after switching, sometimes gives me a feeling that not everything has been done correctly. I therefore go through the items, even though they are 'ticked off'.

6. Would you like to see the ECL integrated in your aircraft?

It would be a nice addition, but for me not necessary it the current cockpit layout.

Participant 3 (ECL)

1. What operational challenges do you see using the ECL?

1. Philosphy of ECL is imperative to be ready knowledge, especially with other OEM's who might have different filosophy (e.g. prioritizing sequence of alert presentation - or not). 2. Hazard of both pilots going head down into the ECL screen iso one explicitely flying. Can be covered in training and SOP's.

2. To improve the ECL, what features can be added?

Prioritizing of alerts.

3. How did you experience i) the 'touch' manipulation on the ECL and ii) the the 'touch' manipulation of the cockpit (overhead, etc.)?

Works well. One remark: when actioning the MC/MW-combi-button, the MW stays illuminated when an AP-warning is displayed. Even when the respective AP is not engaged.

4. How did you utilise the ECL during the scenarios?

Prioritizing by carefully reviewing the alerts individually, while agreeing with fellow crewmember on this priority; Checklist per checklist. On one occasion, I actioned two WINDOW HEAT switches at a time and tackled their procedures individually. Would have been more 'clean and crisp' if I had done the switch actioning while being in the related checklist to elimiante tendency to mentally 'forget' items. These possible 'omissions' would be tackled by the ECL, yet it is a barrier that is more solid when doing it in a respective manner iso in a combined manner.

5. Please describe your strategy step by step. Consider topics such as:

- How did you prioritize checklists?
- To what extend and why did you analyze checklists beforehand (before starting its completion)?
- Did you complete multiple checklists concurrently or one by one?

Example: i) message arrives through EICAS, ii) I check which checklists show up on the ECL to plan my next steps, iii) etc.

The ECL facilitates to have all checklist readily available instead of wondering through a paper ECL. As an addition, the PF should be flying the aircraft, yet he is more actively into the loop of 'your' actions and where you are in a procedure, or what is left to do. This also helps him in his situational awareness without having to interfere with your actions as PM.

6. Would you like to see the ECL integrated in your aircraft?

> Always positive to this on any large aircraft. From history, I have good system knowledge of this aircraft. I hope this ECL will not drive pilots to make the need for system knowledge on this aircraft obsolete, because it is not... System knowledge is key on a B737, also with an ECL.

Participant 4 (ECL)

1. What operational challenges do you see using the ECL?

> Risk of just following the ECL without sufficiently analyzing the situation first.It is easy to just follow the checklist as they appear on screen, top to bottom, which is not always the best order.

2. To improve the ECL, what features can be added?

> Mechanically; the touch screen was not always responsive to touch, especially at the edges.
>
> It would be nice to have an undo button, or just a back button. A number of times I wanted to go back in the checklist and the only option was to reset the entire checklist.
>
> Also, an extra confirmation before resetting all checklists would be nice, to prevent accidental selection.

3. How did you experience i) the 'touch' manipulation on the ECL and ii) the the 'touch' manipulation of the cockpit (overhead, etc.)?

> Works well, you can select any switch with certainty, but the lack of haptic feedback makes mistakes in selections easier. Especially with guarded switches.

4. How did you utilise the ECL during the scenarios?

> I would:
>
> 1. Fly the airplane. Make sure it is on autopilot again (or hand control to my 'co-pilot')
>
> 2. Analyze the situation, try to see how the indications are related and what the underlying cause could be.
>
> 3. Prioritize the failures in order of urgency
>
> 4. Follow the checklists in that order.

5. Please describe your strategy step by step. Consider topics such as:

- How did you prioritize checklists?
- To what extend and why did you analyze checklists beforehand (before starting its completion)?
- Did you complete multiple checklists concurrently or one by one?

Example: i) message arrives through EICAS, ii) I check which checklists show up on the ECL to plan my next steps, iii) etc.

> It really saved a lot of time to not have to thumb through the QRH. This leaves brain (and hands!) free to work on the problem.
>
> Also, there is a lot less chance of missing a failure when you have multiple failures at once.
>
> Also, the list on EICAS provided a nice summary of the warnings and cautions without having to scan the entire cockpit.

6. Would you like to see the ECL integrated in your aircraft?

Very much so. I think it would greatly improve the handling of no-normal situations. Also for normal operations I can see a smoother workflow when using an ECL

Participant 5 (ECL)

1. What operational challenges do you see using the ECL?

Easy to check what needs to be done, what is irrelevant and what has been completed. Both pilots can read along. Instead one is flying and the other is holding the QRH in his/her hand.

2. To improve the ECL, what features can be added?

A sequence of importance or "try fixing before breaking" option. Such as the DRIVE OFF and SOURCE OFF NNC. The DRIVE OFF NNC was reported first on the EICAS but if I would have done that I would not have the option to try fixing it. And importance as FIRE before FUEL PUMP NNC for example.

3. How did you experience i) the 'touch' manipulation on the ECL and ii) the the 'touch' manipulation of the cockpit (overhead, etc.)?

A touch screen would be nice on a middle MFD for ECL. But a backup hard button is needed for turbulent conditions. I'm not a big fan of the overhead touchscreen because the feel of a knob/switch says a lot about the system you're going to connect/disconnect.

4. How did you utilise the ECL during the scenarios?

Prioritized by color. And then within a color I chose what was sequenced for me. But with the electrical failure I chose the second one first because that one would have given me the generator back if it worked instead of the sequenced first one. Analyze; as above. Choosing a checklist with a bit of logic. But within a checklist I just follow the steps. I did not complete multiple checklists. One by one.

5. Please describe your strategy step by step. Consider topics such as:

- How did you prioritize checklists?
- To what extend and why did you analyze checklists beforehand (before starting its completion)?
- Did you complete multiple checklists concurrently or one by one?

Example: i) message arrives through EICAS, ii) I check which checklists show up on the ECL to plan my next steps, iii) etc.

It helps a lot because you can easily see what is completed and what is irrelevant.

6. Would you like to see the ECL integrated in your aircraft?

Yes. I've been using the ECL now for three years and it is one of the biggest improvements from the 777/787 compared to the paper checklists on the 737. The negative point of the ECL is that you do not know exactly what is on the checklist because of the "closed loops" steps. You only check what you need to do to complete the checklist.

Participant 6 (ECL)

1. What operational challenges do you see using the ECL?

scrolling back and forward thru various v lists

2. To improve the ECL, what features can be added?

side by side reminders

3. How did you experience i) the ‘touch’ manipulation on the ECL and ii) the the ‘touch’ manipulation of the cockpit (overhead, etc.)?

good

4. How did you utilise the ECL during the scenarios?

sequence-ing

5. Please describe your strategy step by step. Consider topics such as:

- How did you prioritize checklists?
- To what extend and why did you analyze checklists beforehand (before starting its completion)?
- Did you complete multiple checklists concurrently or one by one?

Example: i) message arrives through EICAS, ii) I check which checklists show up on the ECL to plan my next steps, iii) etc.

fairly

6. Would you like to see the ECL integrated in your aircraft?

yes,alsoin the 747

Participant 7 (AECL)

1. What operational challenges do you see using the ECL?

multiple pages, although inevitable, reamins an issue ’done’ and ’completed might be confusing to some during the session I noticed during scenario 1 that more amber (indented?) warnings came up , like ’gnd prox sys. I could not recall these or did not know what to do with it.

2. To improve the ECL, what features can be added?

during related failures it could be interesting to couple the failed subsystem to the main failure. We used to have a bus equipment list for example where you could check if ie. the transfer bus fails, what electrical components will you lose? maybe indictor for the relation between failed items. more graphics?

3. How did you experience i) the ‘touch’ manipulation on the ECL and ii) the the ‘touch’ manipulation of the cockpit (overhead, etc.)?

works like a charm. the sides of the screen are hard to manipulate, but we discussed that already

4. How did you utilise the ECL during the scenarios?
Please describe your strategy step by step. Consider topics such as:

- How did you prioritize checklists?
- To what extend and why did you analyze checklists beforehand (before starting its completion)?
- Did you complete multiple checklists concurrently or one by one?

Example: i) message arrives through EICAS, ii) I check which checklists show up on the ECL to plan my next steps, iii) etc.

top to bottom approach (red ones first)
Try to assess before going into any checklist what the main failure is. This can only be done when experienced on type
Just slowly and decisevely read everything and tick off the items.

At the hydraulics failure, I tried to speed up the process because I saw an extra item come in indicating an overheat.

6. Would you like to see the ECL integrated in your aircraft?

yes please! I don't think there is enough money for it now because of the Corona crisis. But in the busy day to day operation it would certeinly be a big help to avoid mistakes and suppress workload. Also the automated landing checklist would improve the heads down time during the final approach.

7. Were you comfortable with automating the checklist? If not, why?

absolutely comfortable since I have worked with it on 777/787. You get used to it real quickly

8. How did you experience the dropdown menu of the ECL?

perfect.

9. Did you require to analyze the complete checklist beforehand or were you confident with the feedback presented by the ECL in the menu? If not, what would you like to see changed?

Maybe it is because I had full understanding what the failure was and its relation to all checklists. I did not feel the urge to open any checklist except for the landing distance but that will show up during the deferred items chklist

10. Were you confident with not missing any information when using automation?

very confident. Maybe if you ask a less experienced 737 pilot I can imagine you might want to have more guidance in what is actually the main problem.

Participant 8 (AECL)

1. What operational challenges do you see using the ECL?

The challenge to keep an overview of the different issues and steps which have been taken, especially with a lot of failures presented at once with several unrelated systems affected

2. To improve the ECL, what features can be added?

No features are needed to be added, but I found the way to return to the NN checklists counter intuitive

3. How did you experience i) the 'touch' manipulation on the ECL and ii) the the 'touch' manipulation of the cockpit (overhead, etc.)?

On the ECL, OK
On the cockpit: ok, but I am used to the old fashioned switches

4. How did you utilise the ECL during the scenarios?
Please describe your strategy step by step. Consider topics such as:

- How did you prioritize checklists?
- To what extend and why did you analyze checklists beforehand (before starting its completion)?
- Did you complete multiple checklists concurrently or one by one?

Example: i) message arrives through EICAS, ii) I check which checklists show up on the ECL to plan my next steps, iii) etc.

1: by sequence 2: I followed the sequence provided by the ECL/ECAM 3: most of the time, one by one. If done otherwise, the risk of making faults is to big in my opinion. Humans are not made to multitask, risk of failures becomes to big

6. Would you like to see the ECL integrated in your aircraft?

If could provide a benefit, especially with a huge number of failures presented in the last scenario. However, a scenario like that is not really realistic. The scenarios we use during training/exams are multiple but never with more than 3 or 4 checklists at one. The automated feature of the ECL is a nice benefit.

7. Were you comfortable with automating the checklist? If not, why?

Yes, BUT: maybe it is wise to show which step is being taken by the automation (under the progress bar the step itself to be shown). So the pilot has an overview what is done at that moment

8. How did you experience the dropdown menu of the ECL?

It worked fine

9. Did you require to analyze the complete checklist beforehand or were you confident with the feedback presented by the ECL in the menu? If not, what would you like to see changed?

See my answer 2 questions back

10. Were you confident with not missing any information when using automation?

See my answer three questions back

Participant 9 (AECL)

1. What operational challenges do you see using the ECL?

Becasue the automation steps which are performed by the ECL on long term pilot system knowledge may decrease. Also, because the steps which are perfromed automatically are not shown it is difficult to keep track of the aircraft state and the position of switches.

2. To improve the ECL, what features can be added?

Personally, I would like to see the steps which are performed automatically. This can be done in a gray color scheme for example, just to keep the pilot up to date on the aircraft state and switches.

3. How did you experience i) the ‘touch’ manipulation on the ECL and ii) the the ‘touch’ manipulation of the cockpit (overhead, etc.)?

Very nice, that all worked very well.

4. How did you utilise the ECL during the scenarios?
Please describe your strategy step by step. Consider topics such as:

- How did you prioritize checklists?
- To what extend and why did you analyze checklists beforehand (before starting its completion)?
- Did you complete multiple checklists concurrently or one by one?

Example: i) message arrives through EICAS, ii) I check which checklists show up on the ECL to plan my next steps, iii) etc.

System failures may occur because they are related to other systems. Therefore it is important to start the checklist belonging to the most probable main failure. By doing so, workload can be reduced because previrously failed systems could be repaired by removing their main cause. EICAS helps by prioritizing a little, but a pilot has a better overview of system inter connnection.

6. Would you like to see the ECL integrated in your aircraft?

Yes!

7. Were you comfortable with automating the checklist? If not, why?

Not entirely, because this was my first encounter with a ECL. Furthermore, because system switches were changed automatically and therefore it was more difficult to keep track of aircraft state.

8. How did you experience the dropdown menu of the ECL?

Very nice, user interface was easy and clear.

9. Did you require to analyze the complete checklist beforehand or were you confident with the feedback presented by the ECL in the menu? If not, what would you like to see changed?

I was confident with the feedback presented, however regarding more complex failures it might be better to review all steps.

10. Were you confident with not missing any information when using automation?

See above: Not entirely, but it certainly takes away workload.

Participant 10 (AECL)

1. What operational challenges do you see using the ECL?

-Pilots expending/opening the whole checklist and starting from there.
-The automate button can negatively effect the situation awareness of the pilots. Especially since it directly sets all the items at once (only .5s interval) and the pilots cannot easily follow its steps.
It can be helpful but for several items I think it would still be less workload to change the position of switches themselves. But items like window heat recycle (including the timer) and other short and easy checklists are indeed a good example to automate.

2. To improve the ECL, what features can be added?

A more clear step by step automation, for example:
"The following will be done: - Window Heat L FWD recycle
- Window Heat L AFT recycle

-AUTOMATE-"

3. How did you experience i) the 'touch' manipulation on the ECL and ii) the the 'touch' manipulation of the cockpit (overhead, etc.)?

Good. Nowadays type ratings are more often done for the major part in this way. Only risk I see by doing this with ECL is ticking of items or touching buttons unintentionally by leaning on the surface with a finger or hand palm for example.

4. How did you utilise the ECL during the scenarios?
Please describe your strategy step by step. Consider topics such as:

- How did you prioritize checklists?
- To what extend and why did you analyze checklists beforehand (before starting its completion)?
- Did you complete multiple checklists concurrently or one by one?

Example: i) message arrives through EICAS, ii) I check which checklists show up on the ECL to plan my next steps, iii) etc.

First warnings, then cautions.
In case of a whole list trying to determine which one might be the cause for the others; do this one first
I did it generally one by one, but while a timer was running for an automated recycling the window heat, I continued with the next one.

6. Would you like to see the ECL integrated in your aircraft?

Yes. I am already used to them on the B787 and it is a great feature which reduced workload and generally improved situational awareness because of the overview and closed loop checks.

7. Were you comfortable with automating the checklist? If not, why?

Partly; see before

8. How did you experience the dropdown menu of the ECL?

Good. Just missing a short summary of the (automated) items which are on the expended one as explained before.

9. Did you require to analyze the complete checklist beforehand or were you confident with the feedback presented by the ECL in the menu? If not, what would you like to see changed?

Only once but this should improve while gaining experience with checklists like these and after completing a type rating or training course. See answer above.

10. Were you confident with not missing any information when using automation?

See above

Participant 11 (AECL)

1. What operational challenges do you see using the ECL?

working with it, it’s different from what we are used to do, so this will take some time

2. To improve the ECL, what features can be added?

cannot think of something at this time

3. How did you experience i) the ‘touch’ manipulation on the ECL and ii) the the ‘touch’ manipulation of the cockpit (overhead, etc.)?

once you get used to it , very good

4. How did you utilise the ECL during the scenarios?
Please describe your strategy step by step. Consider topics such as:

- How did you prioritize checklists?
- To what extend and why did you analyze checklists beforehand (before starting its completion)?
- Did you complete multiple checklists concurrently or one by one?

Example: i) message arrives through EICAS, ii) I check which checklists show up on the ECL to plan my next steps, iii) etc.

By doing the warnings(red) first and then the cautions. from top to bottom, you will have to do them all anyway. checking the failure with the overhead panel, to see if the checklist makes sense.
I completed them one by one.

6. Would you like to see the ECL integrated in your aircraft?

I think it is a good idea there will be challenges implicating it, as pilots need to get used to it. automating it will be difficult since the 737 is an old platform. but overall it will be a very nice tool to work with

7. Were you comfortable with automating the checklist? If not, why?

yes was comfortable, but did always check if the respective switches were moved

8. How did you experience the dropdown menu of the ECL?

took me some time to get used to it, and once again it worked great

9. Did you require to analyze the complete checklist beforehand or were you confident with the feedback presented by the ECL in the menu? If not, what would you like to see changed?

it was good en very nice and easy, but we are trained to always double check the automation, so in this case I like to see what is in the whole checklist

10. Were you confident with not missing any information when using automation?

see above

Participant 12 (AECL)

1. What operational challenges do you see using the ECL?

The automation seems to work very well, however, an overview of the steps that were executed (or switches that were operated) might be nice. It keeps the pilots more in the loop of the system status.
Depending on the location in the cockpit, there might be a danger of the pilot monitoring becoming too focused on the checklist without the possibility of the pilot flying to once in a while check what's the status of the checklist reading. An active pilot monitoring will try to keep his/her colleague in the loop, but when workload gets higher this can become an issue. The location in the experiment, however, allows for both pilots to keep an eye on the checklists (even when the pilot flying his main focus lies on flying the aircraft).

2. To improve the ECL, what features can be added?

Give an overview of the steps/switches affected by the automation process. I would be happy with an overview of the switches that were operated after completion. This would increase situational awareness and keeps the pilots better in the loop with the aircraft.

Another addition might be to checklists taking more time to complete the automation part. For example when the automation part takes 2 minutes (as with the WINDOW HEAT cl), it might me useful to add the time to the overview screen (when the checklist is closed before completing it). This adds an additional reminder to revisit the checklist to complete it and it does not require to open the checklist again only to see that another minute is left on the timer.

3. How did you experience i) the ‘touch’ manipulation on the ECL and ii) the the ‘touch’ manipulation of the cockpit (overhead, etc.)?

i) The touch screen on the ECL was fine. Once you know where to touch it worked flawlessly. ii) With the proper technique it was easy to operate the cockpit ’buttons and switches’

4. How did you utilise the ECL during the scenarios?
Please describe your strategy step by step. Consider topics such as:

- How did you prioritize checklists?
- To what extend and why did you analyze checklists beforehand (before starting its completion)?
- Did you complete multiple checklists concurrently or one by one?

Example: i) message arrives through EICAS, ii) I check which checklists show up on the ECL to plan my next steps, iii) etc.

I prioritized mainly using the same priorities the system uses: Warning, caution, advisory. And before starting to solve, a quick scan through the cockpit to see if no vital systems are affected without the ECL showing them. I did only scan quickly through the checklist that was presented before starting to work it through. Mainly to see if there is a ’white box’ and/or ’automation’ button available. When one of the checklists showed a specific duration I continued to the next checklist. After completing them I returned to the previously left checklist to complete it.

6. Would you like to see the ECL integrated in your aircraft?

I very much would like to see this! I think it can reduce the workload a lot, especially when dealing with issues that require a lot of checklists to browse through. The QRH in use now can be quite a handful when you need to switch to different checklists (especially with deferred items in use).

7. Were you comfortable with automating the checklist? If not, why?

I trusted the automation process, but I did check briefly what switches were operated after the automation was finished. Being kept in the loop is important to keep situational awareness at the right level.

8. How did you experience the dropdown menu of the ECL?

I liked the dropdown menu. It reduces the amount of touches needed. However, if you don’t pay attention you might inadvertently open another checklist than the one you initially wanted to open.

9. Did you require to analyze the complete checklist beforehand or were you confident with the feedback presented by the ECL in the menu? If not, what would you like to see changed?

I did not review the entire completed checklist. When checking the system status afterwards I was confident the right steps were taken. As addressed earlier, an overview of the switches/buttons affected in the automation process might be useful.

10. Were you confident with not missing any information when using automation?

Yes, however, a quick glance on the overhead panel gave me additional confirmation that the expected steps were executed.

O

Open Loop Question Analysis

Open Question Result Analysis – Drive Shaft Failure

		ECL						AECL					
		1	2	3	4	5	6	7	8	9	10	11	12
Correct failure recognition? (1)		5	2	4	3	1	1	2	5	3	3	1	1
	Factor												
Primary	RNAV possible												
	Runway length/availability	1	1	1	1	1	1	1	1	1	1	1	1
	Nearest airport	1	1	1	1	1	1	1	1	1	1	1	1
	Single A/P				1	1			1			1	1
	Score, Primary	2	2	2	3	3	2	2	3	2	2	3	3
Secondary	One AC Source/no APU	1		1	1					1	1		
	Ice/weather, other		1	1	1	1		1	1	1	1	1	1
	Avoid turbulent areas/<30 flaps if crosswind >30kts		1		1					1			
	AFT Pedastal INOP (GPWS, TCAS, RA)												
	Score, Secondary	1	2	2	3	1	0	1	1	3	2	1	1
	Score, Total	3	4	4	6	4	2	3	4	5	4	4	4

(1) Correct failure recognition indication
0 No
1 Yes, but only mentions IDG
2 Yes, but only mentions AC bus
3 Yes, mentions IDG and single AC, but does not mention relation
4 Yes, perfect
5 Somewhat, but strange weight on other systems like window overheat or hydraulics

Consolidated Analysis

	ECL		AECL	
	Average	Median	Average	Median
Score, primary	2.3	2.0	2.5	2.5
Score, secondary	1.5	1.5	1.5	1
Score, total	3.8	4.0	4	4

	ECL Accuracy	AECL Accuracy
RNAV possible	0%	0%
Runway distance/availability	100%	100%
Nearest airport	100%	100%
Single A/P	33%	50%
One AC Source/no APU	50%	33%
Ice/weather, other	67%	100%
Avoid turbulent areas/<30 flaps if crosswind >30kts	33%	17%
AFT Pedastal INOP (GPWS, TCAS, RA)	0%	0%

- Main observation is no consideration of RNAV approval
- Other important observations include clear consideration of runway length and availability and nearest airport
- Also, no participant considered Aft Pedestal INOP light

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Open Question Result Analysis – Hydraulic Leak Failure

		ECL						AECL					
		1	2	3	4	5	6	7	8	9	10	11	12
Correct failure recognition? (1)		1	1	1	1	1	1	1	1	1	1	1	1
	Factor												
Primary	Runway length/availability	1	1	1	1	1	1	1	1	1	1	1	1
	Manual gear extension	1	1	1	1	1	1	1			1	1	1
	Single A/P		1	1		1				1			1
	Fuel	1	1			1		1			1	1	1
	Score, Primary	3	4	3	2	4	2	3	1	2	3	3	4
Secondary	Weather	1	1	1	1	1				1	1	1	1
	Airport distance	1	1					1					1
	Maintenance/commercial		1	1	1						1		
	Score, Secondary	2	3	2	2	1	0	1	0	1	2	1	2
	Score, Total	5	7	5	4	5	2	4	1	3	5	4	6

(1) Correct failure recognition indication
0 No
1 Yes

Consolidated Analysis

	ECL		AECL	
	Average	Median	Average	Median
Score, primary	3.0	3.0	2.7	3.0
Score, secondary	1.7	2.0	1.2	1.0
Score, total	4.7	5.0	3.8	4.0

	ECL Accuracy	AECL Accuracy
Runway distance/availability	100%	100%
Manual gear extension	100%	67%
Single A/P	50%	33%
Fuel	50%	67%
Weather	83%	67%
Airport distance	33%	33%
Maintenance/commercial	50%	17%

- All participants clearly indicated consideration of runway length and availability
- Manual gear extension was generally well considered, however often less consistent in combination with fuel requirements (landing gear is non-retractable)

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