Elevated Levels of Automation for Aircraft System & Flight Plan Management

Reitsma, J.P.

DOI
10.4233/uuid:66da035e-4e94-42d7-85f1-2f47885a786d

Publication date
2025

Document Version
Final published version

Citation (APA)
Reitsma, J. P. (2025). *Elevated Levels of Automation for Aircraft System & Flight Plan Management*. [Dissertation (TU Delft), Delft University of Technology]. https://doi.org/10.4233/uuid:66da035e-4e94-42d7-85f1-2f47885a786d

Elevated Levels of Automation for Aircraft System & Flight Plan Management

JELMER P. REITSMA

Elevated Levels of Automation for Aircraft System & Flight Plan Management

Elevated Levels of Automation for Aircraft System & Flight Plan Management

Dissertation

for the purpose of obtaining the degree of doctor
at Delft University of Technology
by the authority of the Rector Magnificus prof. dr. ir. T.H.J.J. van der Hagen,
chair of the Board for Doctorates
to be defended publicly on Wednesday 11, June 2025 at 15:00

by

Jelmer Pascal REITSMA

Master of Science in Aerospace Engineering,
Technische Universiteit Delft, Delft, Nederland
born in Grootegast, Nederland.

This dissertation has been approved by the

promotor: dr. ir. M.M. van Paassen
promotor: dr. ir. C. Borst

Composition of the doctoral committee:

Rector Magnificus,	chairperson
Dr. ir. M.M. van Paassen,	Technische Universiteit Delft, promotor
Dr. ir. C. Borst,	Technische Universiteit Delft, promotor
Independent members:	
Prof. dr. D. Harris	Coventry University, United Kingdom
Prof. dr. A.R. Pritchett	Penn State University, United States of America
Dr. ir. A.C. in 't Veld,	Technische Universiteit Delft
Prof. dr. ir. L.L.M. Veldhuis,	Technische Universiteit Delft
Prof. dr. ir. J.C.F. de Winter,	Technische Universiteit Delft

Prof. dr. ir. M. Mulder has contributed greatly to the preparation of this dissertation.

Keywords: Human Factors Engineering, Automation, Interface Design, Applied Cognitive Work Analysis, Flight Deck Design, Ecological Design

Printed by: Ipskamp Printing

Cover design: J.P.Reitsma

ISBN 978-94-6473-836-0

An electronic version of this dissertation is available at
http://repository.tudelft.nl/.

Contents

List of Abbreviations

AC Alternating current
ACN Aircraft Classification Number
ACWA Applied Cognitive Work Analysis
ADS–B Automatic Dependent Surveillance Broadcast
AECL Automated Electronic Checklist
AFD Airport Facility Directory
AH Abstraction Hierarchy
AIP Aeronautical Information Publication
AIRMET AIRmen's METeorological information
AMM Airport Moving Map
APU Auxiliary Power Unit
ARFF Aircraft Rescue and Fire Fighting
ATC Air Traffic Control
ATD Alerting and Task Display
ATIS Automatic Terminal Information Service
BTB Bus Tie Breaker
CARS Crew Acceptance Rating Scale
ConOps Concept-of-Operations
CPDLC Controller Pilot Data Link Communication
CTA Cognitive Task Analysis
CWR Cognitive Work Requirement
EAD Engine Alerting Display
ECAM Electronic Centralized Aircraft Monitor
ECL Electronic Checklist
EFB Electronic Flight Bag
EGPWS Enhanced Ground Proximity Warning System
EICAS Engine Indicating and Crew Alerting System
EID Ecological Interface Design
FAN Functional Abstraction Network
FHD Full High Definition
FIR Flight Information Region
FMS Flight Management System
FSSD Functional System Status Display
GPS Global Positioning System
HF High frequency
HSD Horizontal Situation Display
IDG Integrated Drive Generator

ILS	Instrument Landing System
IRR	Information / Relationship Resource
LOA	Level of Automation
MCP	Mode Control Panel
MEL	Miminum Equipment List
METAR	METeorological Aerodrome Report
MFD	Multiple Function Display
MFM	Multilevel Flow Modeling
MOCA	Minimum Obstacle Clearance Altitude
MSA	Minimum Sector Altitude
MUH	Minimum Use Height
NAVAID	NAVigational AID
NC	Normal Checklist
ND	Navigation Display
NNC	Non-Normal Checklist
NOTAM	Notice to Airmen
OANS	On-Board Airport Navigation System
PCN	Pavement Classification Number
PDC	Presentation Design Concept
PF	Pilot Flying
PFD	Primary Flight Display
PIREP	PIlot REPort
PNF	Pilot Non-Flying
QRH	Quick Reference Handbook
RAAS	Runway Awareness and Advisory System
RCO	Reduced-Crew Operations
RDR	Representation Design Requirement
RNAV	Area navigation
ROPS	Runway Overrun Prevention System
RSME	Rating Scale Mental Effort
RVSM	Reduced Vertical Separation Minima
SA	Situation Awareness
SART	Situation Awareness Rating Technique
SID	Standard Instrument Departure Route
SIGMET	SIGnificant METeorological information
SOP	Standard Operating Procedures
SPO	Single-Pilot Operations
SRK	Skill, Rule, Knowledge
SRS	Simona Research Simulator
STAR	Standard Arrival Route
SVS	Synthetic Vision System
TAF	Terminal Aerodrome Forecast
TCAS	Traffic Collision Avoidance System
TVSD	Time and Velocity Situation Display

UHD Ultra High Definition
VHF Very high frequency
VSD Vertical Situation Display
WDA Work Domain Analysis
XGA Extended Graphics Array

Summary

Handling high workload is a key concern when implementing Reduced-Crew Operations (RCO). Research has shown that both checklist completion time and decision-making performance suffer when reducing the crew complement from two to one. Although automation has historically been used to address workload issues, it has introduced its own set of challenges. Therefore, allocating more tasks to automation with the aim to lower workload may amplify adverse side effects instead of solving any. Instead, automation should be designed to increase the performance of the human-machine system as a whole.

RCO presents an opportunity to critically reassess automation on the flight deck by redefining the role of the pilot. Many researchers agree that the pilot remains the ultimate decision-maker and is responsible for ensuring the safety and success of the flight operation. The pilot's role will encompass flight planning, communication, and surveillance, while system management tasks are considered suitable candidates for automation. However, automating system management may lead to diminished system state awareness, potentially compromising flight plan management performance. Consequently, additional support is needed to keep the pilot actively engaged with flight plan management tasks.

In addition to addressing the potential adverse effects of automating system tasks, the current support for flight plan management requires already a significant improvement. A key challenge in handling non-normals lies in assessing and integrating disturbances into the flight plan. Pilots must gather, combine, and analyze environmental and system information. This information is often fragmented across multiple sources and requires decryption to become actionable. This process heavily relies on the pilot's initiative and experience, increasing the risk of unconsidered impacts.

This study examined the impact of elevating the Level of Automation (LOA) for system and flight plan management functions. A proposed concept elevated the LOA of the system management support, specifically the action execution stage from a step-by-step action support to a system that autonomously performs a sequence of actions after human activation. In flight plan management, the information acquisition and analysis stages were highly automated, with the goal of reducing workload while enhancing decision-making performance.

A preliminary assessment of the benefits of elevated automation levels for system management estimated that 39% of all checklist items could be automated. The potential time and workload savings were evaluated through the design of an 'Automated Electronic Checklist', which allowed pilots to command the automated execution of non-flight control and automatable items. The checklist was designed so that pilots could review and manually execute the steps if desired. Checklist completion times were found to be reduced similar to what was estimated initially. The initial estimate of automatable checklist items thus appears to be a reliable predictor of reduced completion times. The experiment indicated no adverse effects on decision-making outcomes; pilots with the introduced automation made decisions comparable to those using baseline systems. However, in both cases, decisions were made without fully understanding certain hazards or operating rules. This highlights the ongoing need to enhance flight plan management support during non-normal operations.

Design of a decision support system for a complex work domain, such as commercial aviation, requires an extensive analyses to determine what needs to be presented to support effective decision making for the operator and avoid overloading the pilot with irrelevant information. A framework called Applied Cognitive Work Analysis (ACWA) was used to determine what information needs to be portrayed on the displays. This method is especially designed for the development of decision-making supports and follows a clear step-wise approach. The first step is to map functions and goals of a work domain with the Functional Abstraction Network (FAN). The aim is to identify abstract elements, inspired by how humans process information, to manage and organize information with respect to the operator's goals.

The primary abstract elements identified for managing flight operations and addressing operational impacts are paths and spaces. Each system and environmental condition can either enable or destruct these paths and spaces (e.g., activating anti-ice protection systems enables operation through certain weather conditions like clouds). The pilot's role in flight management is to choose a path that continues to meet key goals such as safety, compliance, cost efficiency, passenger comfort, or adherence to the airline schedule. This is achieved by selecting a route within the available operating space. Pilots can expand operational space by requesting permissions (communication), adjusting the route (flight plan management), or activating specific systems like anti-ice protection (system management).

It was found that an overview of these effects on space and paths is what is needed to support in-flight replanning effectively. Hence, multiple displays were developed to present the effects of a disturbance on a space and path level, which are: a horizontal situation display, a vertical situation display, a time and velocity situation display and a functional overview of the system state.

These displays were experimentally tested with four different scenarios and 32 airline pilots. It was found that pilots were able to make more well-informed decisions with the space and path information presentation. The concepts were well received and the general consensus was that the concepts supports current operation well. It was observed that pilots were more actively involved with replanning.

It was found that pilots struggled to reliably translate cryptic SIGnificant METeorological information (SIGMET) messages, which typically present hazards using coordinates, into actual locations on a map. These misinterpretations resulted in overlooked options and subsequently less informed decisions with the current displays. The concept displays, however, visualized hazardous areas directly on the map, enabling pilots to clearly identify where the impact was and take appropriate precautions accordingly.

Although, color-coding airports and airspaces proved to be a very powerful tool. Pilots exhibited signs of confirmation bias and over-reliance, sometimes avoiding areas or airports without fully understanding the underlying reasons. This suggests that the information must be highly reliable, and pilots need to be trained to critically assess the data or actively verify specific sources. Nonetheless, there is a risk that these additional tasks might lead to cognitive overload, potentially negating the time reductions achieved through system automation.

The main conclusion of this research is that automating system configuration tasks can reduce checklist completion times without introducing significant adverse effects, provided that the impacts are clearly communicated. Additionally, the flight management support demonstrated that while pilots become more engaged in replanning and make more informed decisions, this does not necessarily translate into faster decision-making. Translating system capabilities and environmental conditions into space and path effects has proven effective in enhancing decision quality. Integrating both concepts is likely to improve decision-making quality and either reduce or maintain the time required for non-normal scenarios. However, while these advancements may enhance the performance of both current two-pilot crews and RCO pilots, they can never fully replace a highly experienced crew member.

1

Introduction

1.1. Emergence of Commercial Reduced Crew Operations

Reducing costs and environmental impact are the main innovation drivers in aviation today. Achieving efficiency gains in a cost-effective way through the traditional technological ways, such as propulsion, aerodynamics, or structures, is becoming increasingly challenging (Kharina et al., 2016; Zheng & Rutherford, 2020). Consequently, the aviation industry is therefore considering technologically 'easier' strategies to achieve similar gains. One such strategy involves reducing the flight deck crew complement, which is the main rationale behind the much-debated paradigm of Reduced-Crew Operations (RCO) or Single-Pilot Operations (SPO).

The benefits of RCO are predominantly economic and can be categorized as either reducing costs or increasing productivity. It is expected that RCO lead to a reduction in direct operating costs for airlines (Bilimoria et al., 2014; Vu et al., 2018), could unlock business opportunities (Harris, 2007), could mitigate schedule and network issues (Vu et al., 2018), reduce predicted pilot-shortages (Cummings et al., 2016; Johnson et al., 2012; Schutte, 2017), and free up space and weight for additional seats or cargo (Cummings et al., 2016). Interestingly, most commercial airplanes are already designed such that they can be operated by a single pilot in case of an emergency. Therefore, technology does not seem to be the hindering factor for reduced-crew operations (Boy, 2014; Harris, 2007, 2023).

The main concerns with the introduction of RCO, however, remain related to human factors. Commercial air transport has become one of the safest modes of transportation in human history. Any change to this carefully curated ecosystem can result into the unwanted or unexpected introduction of safety hazards. RCO can therefore *only* be introduced if safety levels are improved or kept similar to those of the current dual-pilot operations. The potential safety implications introduced by RCO have been examined by subject-matter experts. They identified that removing or replacing the (social) functions of the co-pilot and/or captain can cause the following issues: (1) the absence of a back-up in the case of a incapacitated pilot leaving the plane uncontrolled, (2) the absence of assistance during high workload peaks, (3) the absence of an error-checker, (4) loss of non-verbal communications in case of remote assistance, (4) diminishing of learning on the job, (6) boredom, and (7) no protective mechanism against suicidal pilots (Boy, 2014; Comerford et al., 2013; Harris, 2007; Schutte, 2017).

A number of studies have quantified the predicted human performance issues related to RCO (Bailey et al., 2017; Etherington et al., 2017, 2016; Kramer et al., 2018a,b). These pilot-in-the-loop simulations provide hard evidence for some of the aforementioned issues. It was observed that pilots, when operating alone, required more time to troubleshoot malfunctions, made less well-informed decisions, and the safety of the flight was compromised compared to the current two-pilot crew. In short, these observations confirm that levels of workload reached an unacceptable level, indicating that some form of assistance (either human or automated) is necessary.

1.2. Reduced-Crew-Operations Issue Mitigation Strategies

Various forms of assistance have been proposed to overcome these issues. Solutions include defining novel Concept-of-Operations (ConOps), designing new equipment, and the introduction of additional automated systems. The future implementation of RCO will likely involve a combination of these approaches.

The ConOps can be considered the overarching solution that drives equipment and automation requirements. Proposed ConOps range from more conservative approaches, such as removing the need for relief pilots on long-haul flights where the aircraft would be temporarily single-piloted during designated portions of the flight, to more revolutionary concepts involving purely single-pilot operations supported by advanced automated systems.

Other proposed ConOps emphasize increased ground assistance. In these concepts, a ground assistant is envisioned in various roles, such as a remote crew member or an advanced dispatcher (Matessa et al., 2017). Additionally, some variations propose that a ground controller could be stationed at each airport to provide local support (i.e., a harboring pilot) (Johnson et al., 2012). Regardless of the approach, these concepts necessitate adaptations to both the flight deck and ground stations (e.g., modifying controls for remote operation).

Other studies have proposed various equipment adaptations to mitigate issues related to incapacitated pilots. These include health monitoring systems, emergency landing systems (Meuleau et al., 2011), and electronic standby pilots (Mollwitz et al., 2014). Additionally, solutions to address challenges arising from a separated crew in scenarios involving enhanced ground support have been proposed, such as advanced communication tools (Lachter et al., 2014a) and new tools for ground stations (Lachter et al., 2014b). These systems are highly dependent on the specific ConOps implemented and carry the risk of becoming obsolete even before they are fully integrated.

In contrast, increased automation to address issues of high workload or boredom is less dependent on specific ConOps and is also relevant to current operations. For instance, a recent incident involving an Airbus A380 demonstrated that troubleshooting multiple system malfunctions can be extremely taxing (Australian Transport Safety Bureau, 2013). During this incident, an uncontained engine failure caused damage to numerous systems, leading to a large number of alert messages on the flight deck. It took a crew of five over 90 minutes —“an inordinate amount of time” (Mosier et al., 2017, p. 1)— to troubleshoot and complete an emergency landing successfully.

This example highlights that not only would RCO flight decks benefit from increased automated assistance, but current flight decks could also gain from enhanced levels of automation support. In other words, a re-evaluation of flight deck automation and support systems is necessary to address workload-related challenges, even in today's operations (Bailey et al., 2017; Boy, 2014; Harris, 2007).

1.3. Automation as Key Enabler

Increased flight deck automation is a common theme across RCO concepts. However, the specifics of what this workload-reducing automation will look like remain unclear. To date, no studies have proposed designs or evaluated prototypes for this 'increased automation.' Therefore, this research aims to address this gap by designing and evaluating future flight deck automation solutions that are relevant for a variety of ConOps for RCO as well as for current operations. But what exactly is meant by *"increased automation"*, given that automation is a relatively general term?

1.3.1. Automation Defined

Automated assistance can take many forms, so distinguishing between different types of automation can be helpful. Automation is *"an automatically controlled operation of an apparatus, process, or system by mechanical or electronic devices that take the place of human labor"* (Merriam-Webster, n.d., Definition 3). According to Lee et al. (2017, p. 358) automation is *"A machine, usually a computer, that performs a task otherwise done by a person"*. However, it is important to recognize the nuances that differentiate automation from tools, support, or aids. Not everything that performs a task on behalf of a human qualifies as automation.

The distinction between tools and automation lies in the level of human involvement required. While tools assist humans in performing tasks, automation can execute tasks independently once initiated, without further human interference. The term 'automation', derived from the ancient Greek word *autos* (self) and suffix -*matos* (thinking, animated, willing), conveys the idea of processes that happen by themselves, without the need for direct human action.

Cognitive support, on the other hand, is designed to simplify tasks, ease cognition, or act as external memory. For example, a map of the world serves as basic cognitive support by storing information prepared by cartographers, offloading the need for human memory. The map helps in determining the locations of various items, but it does not constitute automation. It is merely a tool because it does not change or perform tasks autonomously. However, if the map were capable of filtering information or frequently updating the user's location by itself, it would then be considered automation.

Automation can be categorized by task type and extent to which it performs these tasks, which will be covered next.

Types of Automation

User tasks, and thus potential automation tasks, can be categorized according to the four stages of human information processing. Parasuraman et al. (2000) classify automation based on these stages: information acquisition, information analysis, decision and action selection, and action implementation. They collectively term the first two stages (acquisition and analysis) as information automation, which aims to enhance the operator's perception and cognition. Information automation can characterized as *evaluation* type automation (Norman, 2013). In contrast, the latter two stages (decision and action selection, and action implementation) are classified as *execution* type automation.

Level of Automation

In addition to the type, automation can also be classified by the extent of human involvement, also known as Level of Automation (LOA). The highest LOA corresponds to no human involvement, while the lowest represents complete human involvement. It is important to note that a system at the lowest level of automation is not truly automated but instead provides support. Therefore, automation should be understood as a property of a system that varies across levels for each stage, rather than as a binary concept.

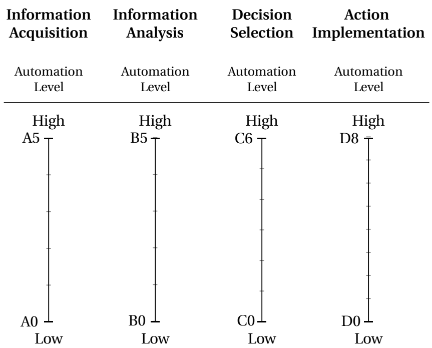


Figure 1.1: Level of automation taxonomy used in this study as presented by (Save & Feuerberg, 2012). See Appendix A for a detailed definition of these levels across each stage.

Level of Automation Taxonomy

Systems can be described in terms of LOA across the four stages of human information processing (Frohm et al., 2008; Kaber & Endsley, 2004; Lee et al., 2017; Parasuraman et al., 2000; Save & Feuerberg, 2012). This study adopts the taxonomy provided by (Save & Feuerberg, 2012), which addresses certain limitations in the classification proposed by Parasuraman et al. (2000). Figure 1.1 depicts this taxonomy, with additional details available in Appendix A. Automation levels begin at level 0, indicating manual task performance, and progress to full automation. At level 1, basic external support for human tasks is provided, such as maps, with automation beginning at level 2 and above. The automation *types* (A–D) are organized horizontally, while the *levels* (0–8) are shown vertically, though not every type includes all levels. Information acquisition and analysis stages do not exceed level 5, while decision and execution stages extend to levels 6 and 8, respectively. A system may be described by different levels within each type (e.g., A5, B5, C6, D6), allowing for detailed descriptions of automation design.

Both types and levels of automation can be combined into a single figure to visualize the 'property' automation in a particular system (as will be done in Section 1.4.2 and Section 1.4.3). These types and levels influence human-machine performance. The automation designer must determine the appropriate level for each type of automation to minimize adverse effects and optimize overall system performance. This leads to an examination of the potential side effects that may be introduced by automation.

1.3.2. Automation and Human Performance Issues

The introduction of automation can enhance the efficiency and productivity of human operators; however, it may also present potential adverse effects. Researchers have long investigated the unintended consequences associated with automation (Bainbridge, 1983; Strauch, 2018). The following provides a brief overview of foreseeable issues that need to be mitigated or minimized during the design phase of automation.

Reliability and Trust

First, there is the issue of reliability. Errors may arise from design flaws, and unforeseen conditions may challenge the automation's ability to function effectively. These factors can impact the perceived reliability of the system and influence the extent to which the automation is trusted and utilized. Trust in automation can vary; excessive distrust may lead to inefficiencies if valuable assistance is disregarded (Lee et al., 2017), while overtrust, or complacency, can occur when users rely on automation for tasks it cannot reliably perform. This overreliance can lead to unexpected issues or failures.

Reduced Situation Awareness & Skill Degradation

Furthermore, automation can lead to what is known as *out-of-the-loop behavior* (Bainbridge, 1983; Lee et al., 2017). Users of automation are often relegated to a supervisory role, which means they are not actively engaged in the control loop. This detachment can lead to difficulties in monitoring and taking manual control when automation fails, particularly after prolonged periods of disengagement. Human monitoring tends to be slower and less accurate, and reduced involvement can diminish situational awareness. As a result, intervening effectively becomes challenging if the operator is out-of-the-loop (Bainbridge, 1983). Prolonged disengagement can also result in skill degradation, both in manual control and cognitive abilities. Generally, as automation levels increase, there is a tendency for both workload and situational awareness to decrease.

Incoherent Set of Tasks

Another issue arises when automation is introduced incrementally as a result of a technology-driven process, rather than as a complete system. In such aircraft, operators may be left with a fragmented set of tasks that automation cannot yet handle or is too costly to automate. Typically, automation is designed to manage specific conditions, often under normal operating circumstances, leaving more complex and challenging situations to human control. Consequently, the pilot often acts as an exception handler (Schutte, 2017). This contributes to 'out-of-the-loop behavior,' as pilots may not be fully aware of which tasks are automated and which are not. To mitigate these problems and minimize distractions, it is crucial to ensure a coherent set of tasks and a well-integrated automation system (Schutte, 2017).

For example, if the pilot's primary responsibility is to fly the aircraft, all tasks directly related to this responsibility should be allocated to the pilot. Tasks unrelated to flying, including those needed during non-normal conditions, should be automated. This approach ensures that the pilot is not burdened with extraneous tasks, allowing them to focus on core responsibilities and building situation awareness through the operation.

Over-automation

Another issue arises when automation is introduced in environments where workload is already low. Optimal human-machine performance occurs at a balanced workload level—not too high and not too low. Over-automation in such contexts can lead to boredom and reduced vigilance, as operators may become disengaged from their tasks.

Adverse Workload Effect

Lastly, managing automation might be cumbersome depending on its implementation. Automation management tasks can completely dissolve the net saving of workload, to a point that the original task is replaced by the managing automation task (e.g., configuring the system). In this case the task is not taken over but changed.

Understanding these issues is crucial when designing new automation. As the LOA increases, the potential for adverse effects on the operator's performance also grows. To mitigate these issues, it is essential to systematically allocate functions between the operator and the automation, and to make deliberate choices regarding the type and level of automation.

1.4. Designing Automated Flight Deck Support Systems

RCO presents an opportunity to redesign flight deck automation and support systems by re-evaluating the pilot's role and strategically allocating functions to support this role (Harris, 2007). A key question guiding this process is: "What should, and what should specifically *not*, be automated to enhance human performance while minimizing adverse effects?" The approach taken in here to address this question is outlined below.

1.4.1. Functional Allocation Strategy

It may be tempting to adopt an approach where automation takes over the role of the pilot monitoring. However, as pointed out earlier this can result in the pilot being left with a set of inconsistent tasks to manage, resulting in 'out-of-the-loop' behavior.

Another common approach to allocate tasks is to use Fitt's list, also known as the "HABA-MABA" (Humans Are Better At - Machines Are Better At) approach, for task allocation (Fitts, 1951). This method assigns tasks to the system component best suited for them. However, while Fitt's list can serve as a starting point, it often results too in a fragmented set of tasks. Thus, it should not be relied upon as a comprehensive design guide (Boy, 2014; Schutte, 2017).

Instead, this research follows the guideline that *"functions should be shared between the person and the automation so that the person is left with a coherent set of tasks that he or she can understand and respond to when the inherent flexibility of the person is* *needed"* (Lee et al., 2017, p. 373). This approach will inform the allocation of functions on the flight deck and the envisioned role of the pilot.

Flight Deck Functions

A prerequisite for effective function allocation is a clear understanding of the functions that need to be performed. Several studies offer function categorizations, but this study will use the framework proposed by Abbott (1993), as it is considered the most comprehensive. According to Abbott, the key flight-deck functions are:

- **Flight Management**: This function involves managing all parameters related to flight guidance and control, including navigation, planning and maneuvering the aircraft.
- **Communications Management**: This function pertains to overseeing the flow of information between systems, including both internal communications (within the aircraft) and external communications (with air traffic control and other external entities).
- **Systems Management**: This function involves managing aircraft systems with operational states or modes that can be externally controlled in a predetermined manner, ensuring these systems operate correctly and efficiently.
- **Task Management**: This overarching function involves managing the tasks and associated resources required to conduct the mission, ensuring all necessary activities are coordinated and effectively executed.

Envisioned Role of the Pilot

According to Bilimoria et al. (2014) *"the human pilot is the ultimate decision-maker on board the aircraft and is responsible for ensuring a successful and safe outcome of the flight operation."* In line with this perspective, Harris (2007) proposes a redefined role for the pilot, suggesting that *"the role of the pilot will be that of a flight planner (both on a strategic and tactical level); a communicator with ATM facilities, and a surveillance operative."* When unforeseen events arise, the human pilot is expected to adapt and address these situations, and, in certain instances, manually control the aircraft (Harris, 2007; Schutte, 2017). Harris (2007) emphasizes that the pilot's responsibilities should focus on flight management, particularly flight plan management, task management, and communication, while system management is deemed less critical and thus a potential candidate for automation. This viewpoint is supported by Boy (2014) and Cummings et al. (2016).

Schutte (2017) argues that emphasis should be placed on a combination of flight management and task management. The main reasoning behind this is to keep the pilot engaged in what matters most, where no skill loss is tolerated, ensuring they are prepared when needed most (i.e., flight control). The pilot should frequently take over manual control, and the automation should be designed to facilitate this process easily. The automation should be capable of handling dynamic task allocations. While the pilot will remain engaged, if the situation becomes overwhelming, they can easily offload tasks to automation. Hence, the RCO flight deck should extensively support the task management function, as dynamic task allocation may be a promising countermeasure to reduce skill degradation.

Based on these perspectives, the approach adopted in this study is as follows: Firstly, the system management function appears to be a suitable candidate for workload reduction, which is required for RCO. However, it is anticipated that the introduction of automation may lead to degraded system state awareness, as the pilot's engagement reduces when the system manages itself [1]. This reduction in engagement could potentially compromise the pilot's operational decision-making performance. Therefore, to mitigate the adverse effects of increased automation and maintain or enhance decision-making performance compared to current day systems, the flight plan management function should receive increased support. This design approach will be elaborated in the following sections.

1.4.2. Reducing Workload Through System Management

Pilots typically follow checklists and often lack the necessary system knowledge or state awareness to make informed decisions to deviate from established procedures. Deviations from these procedures are generally discouraged. Harris (2007, p. 522) notes, *"In the case of a system malfunction, there is little that the pilot can do to rectify the situation."* Pilots are not trained engineers and do not have the time to fully diagnose a complex system or devise creative solutions while in flight, particularly when they are alone in the cockpit. And relying on pilots to verify the correctness of these procedures has not proven effective, as demonstrated by Davis & Pritchett (2000). Therefore, system management is largely rule-based, leaving pilots with limited decision-making beyond accepting or rejecting the prescribed corrective actions, not utilizing human's unique key strengths.

Furthermore, aircraft systems and automation are designed to detect abnormalities more quickly and accurately than humans can. Automation is highly effective at stabilizing internal systems to mitigate deterioration (Harris, 2007). In fact, a significant portion of the system is already automated. Cummings et al. (2016, p. 2) states, *"Many but not all items in an electronic checklist are automatically sensed and set, and it often appears to pilots that there is 'no rhyme or reason' for what is or is not automated."*

Therefore, system management is a promising candidate for increased automation to reduce workload. Current system management support can automatically sense and analyze the system state, as illustrated in Figure 1.2. Error handling is primarily managed through systems such as the Engine Indicating and Crew Alerting System (EICAS) and Electronic Checklist (ECL) in Boeing architectures, and the Electronic Centralized Aircraft Monitor (ECAM) in Airbus architectures. These systems display and prioritize abnormal system conditions and recommend corrective actions. A key difference between ECL and ECAM is that with ECL, the pilot retains the ability to decide the order of checklist execution, although execution is manual in both systems. Nonetheless, there will always be items that cannot be detected by these systems, such as a crack in a window (i.e., unannunciated failures).

[1] Situation awareness drives decision-making performance (Endsley et al., 2003), and increased automation often leads to reduced situation awareness. Consequently, high levels of automation are likely to result in degraded decision-making performance.

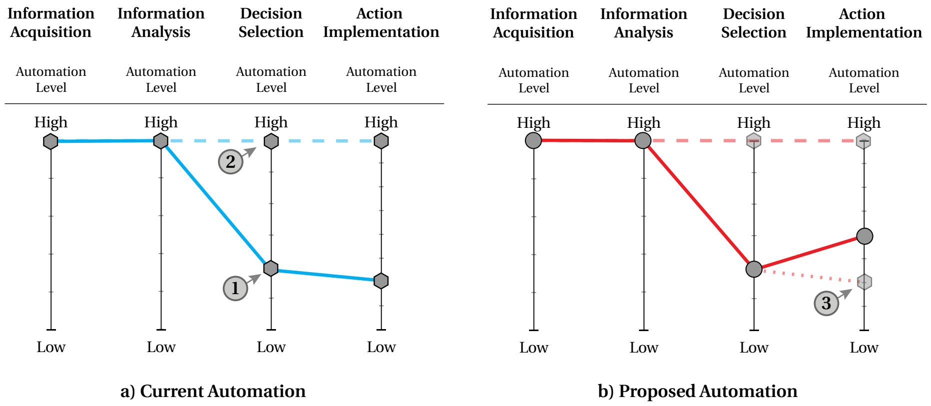


Figure 1.2: System management in commercial aviation is highly automated at the 'information' stages, with synoptics, overhead panels, displayed dials, and indicators providing extensive support during data acquisition. Alerting systems such as (1) EICAS and ECAM notify pilots of non-normal conditions, guiding them through checklists with step-by-step instructions. ECAM, in particular, is designed with a higher level of automation, offering a single corrective option (not depicted). Additionally, modern aircraft feature fully automated systems that require no human intervention (2). The proposed approach is to automate additional steps with pilot approval (3), while flight control tasks will remain manual. For further details on the level descriptions, see Appendix A.

The first part of this research will propose and investigate the effects of elevating the current level D2 to level D4, which is described as: *The system performs automatically a sequence of actions after activation by the human. The human can monitor all the sequence and can interrupt it during its execution*, see Appendix A. This approach allows for potential takeovers, as recommended by Schutte (2017), and maintains some manual actions that cannot be automated, such as closing a door or putting on an oxygen mask. Additionally, certain tasks will be kept manual to ensure human involvement, such as lowering the landing gear, which is crucial for a cohesive flight control task.

1.4.3. Enhancing Flight Plan Management Supports

Secondly, as previously discussed, increased automation in system management is likely to reduce the pilot's awareness of the system state, in the short and long term. While detailed knowledge of the actual *system* state may not be crucial for the pilot, understanding the *implications of the system state* on the mission or operation remains essential for effective flight plan management and operational decision-making (Bailey et al., 2017; Harris, 2007).

For instance, consider a scenario where the aircraft's brakes are malfunctioning. In many cases, such as a brake fluid leak, the pilot cannot repair the issue directly but can only contain the failure to prevent further deterioration and/or switch to a redundant system to restore functionality. Currently, the pilot uses information such as oil pressures or quantities to address predictive questions like, *"Can I regain brake functionality?"* or *"Can I still safely land on the planned runway?"* Why not provide the pilot with direct answers to such questions? Since the pilot primarily deals with the consequences of the malfunction rather than solving it, their main task in non-normal conditions is

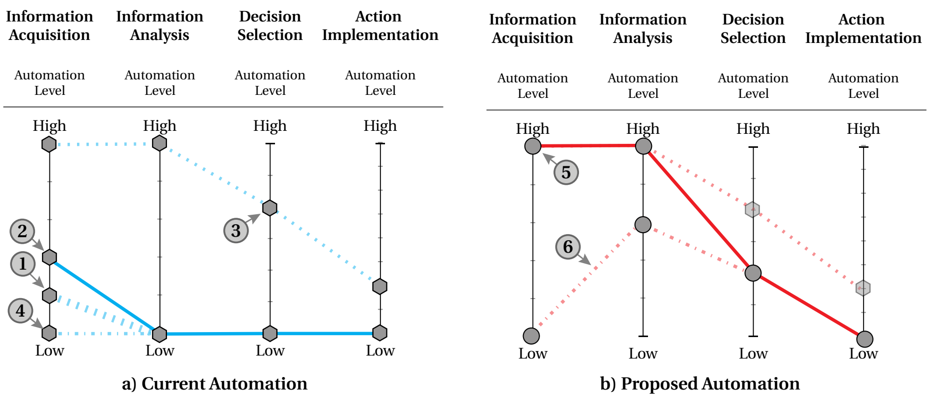


Figure 1.3: Levels of automation for current and proposed flight plan management are lower compared to system management. For example, NOTAMs and TAFs are artifacts (potentially digital) requiring manual processing by the pilot beyond the acquisition stage (1 & 2). This also applies to operational notes presented by ECL. On the other hand, more automated systems like TCAS and EGPWS provide automatic resolutions, though execution remains manual in most airplanes (3). Some information sources, such as reports provided by voice communication, lack digital artifacts altogether (4). The proposed solution aims to elevate most operational impact information to a fully automated level (5), with decision-making retained by the pilot. However, there will always be impacts that the system cannot sense, represented by (6). The execution phase is currently out of scope.

to make decisions that minimize the impact of the failure on the mission.

If the system management function is fully automated, the pilot may be unaware of the operational impacts, as they are neither involved in monitoring nor rectifying the systems. Consequently, these operational implications need to be presented explicitly. Currently, the limitations and consequences of system failures are insufficiently addressed on flight decks (Mumaw et al., 2018b; Reitsma et al., 2017). While such information can be found in the Quick Reference Handbook (QRH) and operation manuals, retrieving these implications relies on the pilot's initiative and experience (Bailey et al., 2017; Mumaw et al., 2018a; Reitsma et al., 2017). Therefore, presenting the implications of system states on the mission could significantly reduce workload —-by eliminating the need to search for information in manuals and perform calculations—-while also maintaining or enhancing decision-making performance compared to current support systems (Harris, 2007). Providing predictive system status information has been shown to reduce workload and enhance decision-making performance. It is therefore expected that offering predictive information at a flight plan level will enable pilots to transition from reactive to proactive behavior (Pritchett & Ockerman, 2016; Trujillo, 1998).

Previous efforts were undertaken by Dinadis & Vicente (1999) to design displays showing the implications of system states on the remainder of the flight, providing information across all functional levels, including higher goals and impacts like range and status. However, the display primarily focused on system management and diagnosing failures, which is inconsistent with the envisioned role of the future RCO pilot.

Flight plan management support on current flight decks is illustrated in Figure 1.3.

Notably, there is a broad range in LOA, ranging from no presentation of potential impacts or operational notes to integrated resolution advisories for collision avoidance. However, these higher-level systems primarily address tactical flight guidance, while the majority of impact determination on the flight plan is still performed manually.

Therefore, the second part of this study will investigate the effects of providing the pilot with an operational overview which s/he can use to make operational decisions (see Figure 1.3). The LOA for this flight management support will mainly be elevated for the information acquisition and analysis types. The proposed automated support will therefore be of the type 'information automation', a typical decision-making support. The proposed system will search, integrate and transform information to operational relevant information automatically (on level A5 and B5). However, this automation relies on the human to make all the decisions, since the pilot will likely be a better-suited decision-maker for an uncertain and dynamic operating environment due to the pilot's knowledge about the complex and ever-changing world, and not to forget his or her intuition. Skill-degradation or out-of-the-loop behavior is expected to occur if decisions would be made automatically. Studies proofed that overreliance on the automation is a concern, if a fully detailed plan is generated by the automation (Chen & Pritchett, 2001). Hence, the human is kept involved to generate the options him/herself within the operating space.

1

1.5. Research Objective and Guiding Questions

This research will investigate two types of automation: system management support and flight plan management support.

To date, there are no known published studies that have designed or evaluated these specific automated solutions in a holistic manner. Therefore, this project aims to design and assess these two types of automated supports to quantify their effects on human performance and determine if this approach is fit for future implementations. The main research objective of the project is:

Research objective

Enhance the modern commercial flight deck, by elevating the levels of automation on system management and flight plan management, to reduce workload while improving decision-making performance.

This objective is achieved in steps, with each step guided by a question:

Guiding questions

1. What are the human performance challenges related to flight plan management and how is this supported by current flight deck systems?
2. What are the potential gains in terms of task reduction for the envisioned system management automation?
3. What is the impact on human performance if system management would be increasingly automated?
4. What information is needed to effectively support operational decision making?
5. What would the flight deck look like if it would focus on supporting operational decision making?
6. What is the impact on human performance if the pilot is provided with an operational decision-making support?

1.6. Assumptions and Scope

A number of assumptions have been made to scope the project, which are:

- It is assumed that all interfaces can be redesigned without restriction; certification requirements are not taken into consideration.
- The proposed automation is targeted for newly developed flight deck architectures. It is assumed that the information and technology needed that drive these automa-

tion and interfaces is available on the flight deck, such as touch screens, or in the future maybe internet.

- The current information sources –manuals and operating guidelines— available to the pilot are used as basis for the interfaces. Current operational notes and limitations stated in the manuals are transferred to a visual form or display implementation. No system analysis is performed to determine other effects or impacts.

- The flight plan management support in this project is limited to support only the 'bridge of evaluation' as defined by Norman (2013). Hence, the prototype becomes an operational-alerting support. The 'bridge of execution', which can include for example the user interaction to adjust waypoints or pick another airport, is not yet implemented. This is seen as a next step. Some examples of this are provided by Pritchett & Ockerman (2016).

- The Boeing 737 systems are used as a baseline for all the concepts and prototypes, mainly due to pragmatic reasons. The Boeing 737 series is chosen for its availability of technical documentation, access to simulators and availability of pilots. However, the Boeing 737 is a legacy aircraft and is not equipped with 'modern' flight deck supports like EICAS or ECL. To start off with a 'modern' set-up, the Boeing 737 systems (back-end) are complemented with the Boeing 787 flight-deck suite (front-end), including EICAS and ECL. This non-existing aircraft will be further referred to as the Boeing 737 Modernized.

- Identifying crew incapacity and implementing appropriate responses to such scenarios also require automated systems; however, this issue falls outside the scope of the thesis.

1.7. Thesis Outline

This thesis consists of seven chapters. The outline is visualized in Figure 1.4.

Chapter 2 serves as the foundation for the rest of the chapters by answering preliminary questions. It outlines the challenges of flight plan management based on the current status quo and provides a preliminary quantification of the benefits of the newly designed automation before any concepts are produced. This preliminary estimation allows for a theoretical aiming point, enabling evidence-based design choices at an early stage. Both guiding questions 1 and 2 will be addressed in this chapter.

In **Chapter 3**, the system management automation is designed and evaluated based on preparatory work. This chapter includes both the design results and the evaluation through a human-in-the-loop experiment for this system management automation. A basic engineering approach is taken for the design, consistent with the previously presented function allocation. Guiding question 3 will be covered in this chapter.

From **Chapter 4** onwards, the design and evaluation of flight plan management support systems will be addressed. Designing automation, such as system management automation, differs from designing decision-making supports, which need to facilitate complex cognitive processes. Thus, a different approach is necessary. The Applied Cognitive Work Analysis (ACWA) method is chosen as the design framework for

1

developing flight management decision supports, and the rationale for this choice is explained in the chapter. The results include a set of objective representation requirements that form the basis for the content of the actual interface, specifying what information should be presented rather than how. In this chapter, guiding question 4 will be discussed.

Chapter 5 provides a detailed description of the newly designed displays, based on the previously derived representation requirements. This chapter explains how these requirements are translated into a visual form. This chapter will address guiding question 5.

Chapter 6 presents the results of a pilot-in-the-loop experiment with the designed supports discussed in Chapter 5. The chapter evaluates and discusses the effects on pilot performance, workload, and situational awareness. This chapter will focus on guiding question 6.

The concluding chapter, **Chapter 7**, discusses observations from both experiments and assesses whether the main objective has been achieved. It reviews and generalizes the results and findings from the experiments and provides recommendations for future research and design efforts.

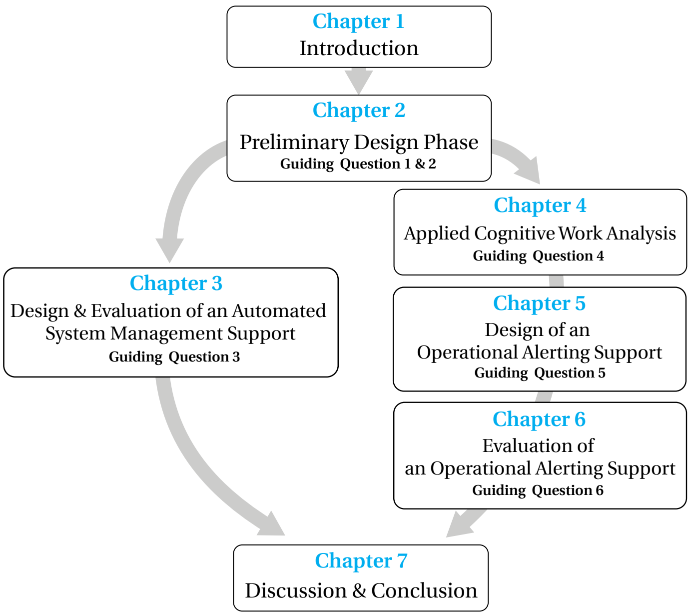


Figure 1.4: Outline of the thesis.

References

Abbott, T. S. (1993). *NASA-TM-109005 Functional categories for future flight deck designs*. Technical report, NASA Langley, Hampton, Virginia.

Australian Transport Safety Bureau (2013). *In-flight uncontained engine failure A380-842, VH-OQA*. Technical Report AO-2010-089, Australian Transport Safety Bureau, Canberra.

Bailey, R. E., Kramer, L. J., Kennedy, K. D., Stephens, C. L., & Etherington, T. J. (2017). An assessment of reduced crew and single pilot operations in commercial transport aircraft operations. In *AIAA/IEEE Digital Avionics Systems Conference - Proceedings*.

Bainbridge, L. (1983). Ironies of automation. *Automatica*, 19(6), 775–779.

Bilimoria, K., Johnson, W., & Schutte, P. (2014). Conceptual framework for single pilot operations. In *Proceedings of HCI-Aero 2014* (pp. 1–8). Santa Clara, California: Association for Computing Machinery.

Boy, G. A. (2014). Requirements for single pilot operations in commercial aviation: A first high-level cognitive function analysis. *CEUR Workshop Proceedings*, 1234, 227–249.

Chen, T. L. & Pritchett, A. R. (2001). Development and evaluation of a cockpit decision-aid for emergency trajectory generation. *Journal of Aircraft*, 38(5), 935–943.

Comerford, D., Brandt, S. L., Lachter, J., Wu, S.-C., Mogford, R., Battiste, V., & Johnson, W. W. (2013). *NASA's Single-Pilot Operations Technical Interchange Meeting: Proceedings and Findings*. Technical Report NASA/CP—2013–216513, NASA, Moffett Field, CA.

Cummings, M. L., Stimpson, A., & Clamann, M. (2016). Functional Requirements for Onboard Intelligent Autom ation in Single Pilot Operations. In *AIAA Infotech@ Aerospace*, number January (pp. 1652).

Davis, S. D. & Pritchett, A. R. (2000). Alerting System Assertiveness, Knowledge, and Over-Reliance. *Journal of Information Technology Impact*, 1(3), 119–143.

Dinadis, N. & Vicente, K. J. (1999). Designing Functional Visualizations for Aircraft Systems Status Displays. *International Journal of Aviation Psychology*, 9(3), 203–223.

Endsley, M. R., Bolte, B., & Jones, D. G. (2003). *Designing for Situation Awareness: An Approach to User-Centered Design*. CRC Press.

Etherington, T. J., Kramer, L. J., Bailey, R. E., & Kennedey, K. D. (2017). Quantifying Pilot Contribution to Flight Safety During an In-Flight Airspeed Failure. In *International Symposium on Aviation Psychology (ISAP); 19th; 8-11 May 2017; Dayton, OH; United States*.

1

Etherington, T. J., Kramer, L. J., Bailey, R. E., Kennedy, K. D., & Stephens, C. L. (2016). Quantifying pilot contribution to flight safety for normal and non-normal airline operations. In *AIAA/IEEE Digital Avionics Systems Conference - Proceedings*.

Fitts, P. (1951). *Human engineering for an effective air-navigation and traffic-control system*. Technical report, Ohio State University Research Foundation.

Frohm, J., Lindström, V., Stahre, J., Winroth, M., Johansen, J., & Johansson, C. (2008). Levels of Automation in Manufacturing. *Ergonomia - an International journal of ergonomics and human factors*, 30(3).

Harris, D. (2007). A human-centred design agenda for the development of single crew operated commercial aircraft. *Aircraft Engineering and Aerospace Technology*, 79(5), 518–526.

Harris, D. (2023). Single-pilot airline operations: Designing the aircraft may be the easy part. *Aeronautical Journal*, 127(1313), 1171–1191.

Johnson, W., Lachter, J., Feary, M., Comerford, D., Battiste, V., & Mogford, R. (2012). HCI Aero 2012 Task Allocation for Single Pilot Operations: A Role for the Ground. In *Proceedings of HCI Aero 2012*.

Kaber, D. B. & Endsley, M. R. (2004). The effects of level of automation and adaptive automation on human performance, situation awareness and workload in a dynamic control task. *Theoretical Issues in Ergonomics Science*, 5(2), 113–153.

Kharina, A., Rutherford, D., & Zeinali, M. (2016). Cost assessment of near and mid-term technologies to improve new aircraft fuel efficiency. *The International Council on Clean Transportation*, (pp.60).

Kramer, L. J., Etherington, T. J., Bailey, R. E., & Kennedy, K. D. (2018a). Quantifying Pilot Contribution to Flight Safety during Drive Shaft Failure. In *Advances in Intelligent Systems and Computing*.

Kramer, L. J., Etherington, T. J., Bailey, R. E., & Kennedy, K. D. (2018b). Quantifying pilot contribution to flight safety during hydraulic systems failure. In *Advances in Intelligent Systems and Computing*.

Lachter, J., Battiste, V., Matessa, M., Dao, Q. V., Koteskey, R., Johnson, W. W., & WalterJohnson, N. (2014a). Toward Single Pilot Operations: The Impact of the Loss of Non-verbal Communication on the Flight Deck. In *Proceedings of HCI-Aero 2014* Santa Clara, California.

Lachter, J., Brandt, S. L., Battiste, V., Ligda, S. V., Matessa, M., & Johnson, W. W. (2014b). Toward Single Pilot Operations: Developing a Ground Station. In *Proceedings of HCI Aero 2014* Santa Clara, California.

Lee, J. D., Wickens, C. D., Liu, Y., & Boyle, L. N. (2017). *Designing for People: An introduction to human factors engineering*. CreateSpace.

Matessa, M., Strybel, T., Vu, K., Battiste, V., Schnell, T., & Collins, R. (2017). *Concept of Operations for RCO/SPO*. Technical report, NASA, Moffett Field, CA.

Meuleau, N., Neukom, C., Plaunt, C., Smith, D. E., & Smith, T. (2011). *The Emergency Landing Planner Experiment*. Technical report, NASA, Moffett Field, CA.

Mollwitz, V., Müller-Diveky, S., Offredi, M., Mosquera, D., & Lücke, O. (2014). *ACROSS: Electronic Standby Pilot Concept of Operations*. Technical report, DLR.

Mosier, K. L., Fischer, U., Burian, B. K., & Kochan, J. A. (2017). *Autonomous, context-sensitive, task management systems and decision support tools I: Human-autonomy teaming fundamentals and state of the art*. Technical Report NASA/TM—2017–219565, NASA, Moffett Field, CA.

Mumaw, R. J., Feary, M., & Fucke, L. (2018a). Airplane capabilities: Translating non-normal information for operational decision-making. *2018 Aviation Technology, Integration, and Operations Conference*.

Mumaw, R. J., Feary, M., Fucke, L., Stewart, M., Ritprasert, R., Popovici, A., & Deshmuk, R. (2018b). *Managing Comnplex Airplane System Failures through a Structured Assessment of Airplane Capabilities*. Technical Report NASA/TM-2018-219774, NASA, Moffett Field, CA.

Norman, D. A. (2013). *The Design of Everyday Things*. New York: Basic Books, revised edition.

Parasuraman, R., Sheridan, T. B., & Wickens, C. D. (2000). A Model for Types and Levels of Human Interaction with Automation. *IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans*, 30(3), 286–297.

Pritchett, A. R. & Ockerman, J. J. (2016). Supporting mixed-initiative emergency flight planning by portraying procedure context information. *Cognition, Technology and Work*, 18(4), 643–655.

Reitsma, J., Fucke, L., Borst, C., & van Paassen, M. (2017). Taking a Closer Look at Flight Crew Handling of Complex Failures – Ten Case Studies. In *19th International Symposium on Aviation Psychology (ISAP 2017)* Dayton.

Save, L. & Feuerberg, B. (2012). Designing Human-Automation Interaction: a new level of Automation Taxonomy. (pp. 978–0).

Schutte, P. C. (2017). How to make the most of your human: design considerations for human – machine interactions. *Cognition, Technology and Work*, 19(2), 233–249.

Strauch, B. (2018). Ironies of Automation: Still Unresolved after All These Years. *IEEE Transactions on Human-Machine Systems*, 48(5), 419–433.

Trujillo, A. C. (1998). *Changes in Pilot Bahavior with predictive system status information*. Technical Report 20040086943, NASA Langley Research Center, Hampton, VA, USA.

Vu, K. P. L., Lachter, J., Battiste, V., & Strybel, T. Z. (2018). Single Pilot Operations in Domestic Commercial Aviation. *Human Factors*, 60(6), 755–762.

Zheng, X. S. & Rutherford, D. (2020). Fuel burn of new commercial jet aircraft: 1960 to 2019. *ICCT: The International council on clean transportation*, (September).

2

Preliminary Design Phase

What are the human performance challenges related to flight plan management and how is this supported by current flight deck systems? What are the potential gains in terms of task reduction for the envisioned system management automation?

In this chapter, three initial studies are presented which guide the remainder of the project. Each study provides insight for the upcoming design efforts. The first study describes a more-detailed overview —compared to the overview presented in Chapter 1— of the tasks and challenges pilots encounter in their daily operations. In Section 2.3, the current flight deck support systems are examined on how well the crew is supported to resolve the aforementioned challenges. These findings provide the foundation on how much adaptation of the to-be-designed automation and flight deck supports is desired. And lastly in Section 2.4, a preliminary prediction of the potential task-load savings for automation is provided to determine the feasibility of this novel automation.

Parts of this chapter have been published in:

Reitsma, J. P., van Paassen, M. M., & Mulder, M. (2019). *Operational Alerting on Modern Commercial Flight Decks.* 20th International Symposium on Aviation Psychology, 295-300.

Reitsma, J. P., van Paassen, M. M., Borst, C. & and Mulder., M. (2021). *Quantifying automatable checklist items on a commercial flightdeck. AIAA SciTech 2021 Forum. January 2021.*

2.1. Introduction

In the winter of 2017, the Netherlands experienced high amounts of snowfall due to cold weather conditions and a low-pressure system. A total of twenty centimeters of snow accumulated in a short span of time. This forced Amsterdam Airport Schiphol to cancel six-hundred flights – approximately half of a normal day's take-offs and landings. Only one runway remained in service, but snow kept on accumulating. At 15:11 UTC, the runway closed temporarily to clear the runway from the excessive amount of snow. Consequently, some planes deviated to other airports while others entered the holding pattern. After twenty-seven minutes of circling, the plane first in line was cleared to land at the just-cleared runway. On final, the tower announced that the braking action of the runway had been deteriorated from *medium* to *medium-to-poor*. The crew of the Boeing 737 responded to this announcement by aborting the approach and stated that they needed more time to determine if they could make a safe landing. By this decision, they moved from the first position in the queue to the last, and after thirty minutes they were back on final. They landed safely with a delay of almost an hour, but with confidence that they were able to make a safe landing. Ironically, landing on a runway with inferior conditions compared to the first attempt (i.e., with more accumulated snow on the runway, less fuel reserves, and less daylight).

This example case signifies that in-flight decision making is challenging, even for the current two-pilot crew aided by the current flight-deck support systems. This case is not unique; similar challenging cases occur frequently during daily operations. As was pointed out in Chapter 1, we can expect that such challenges will be amplified for Reduced-Crew Operations (RCO).

Before new automation or supports are designed to resolve these difficulties, an in-depth understanding is needed of: (1) the underlying processes from which these challenges arise, (2) the current support tools available on the flight deck, and (3) the potential gains obtained with automation to reduce workload. The result of these studies will drive the remainder of the project. It further provides insight into the feasibility of the project at a preliminary stage. This chapter presents all these topics in three sections, Section 2.2, Section 2.3, and 2.4, respectively, starting with a deep dive on cognitive challenges pilots encounter on the flight deck.

2.2. Cognitive Demands on the Flight Deck

This section starts with a simple model of the processes and functions on the flight deck presented in Section 2.2.1, and Section 2.2.2, respectively. These processes and functions will be combined to describe how pilots handle in-flight disruptions in Section 2.2.3. Once this has been established, the cognitive challenges encountered by pilots during flight can be highlighted in Section 2.2.4.

2.2.1. States of a Human-Machine System

System states and processes in control systems can be represented by a simple model, which is presented in Figure 2.1. This simple model is inspired on the states of a system within a feedback control loop. The four states will be elaborated upon below.

If the human-machine system is controlled effectively, the system will reach a **steady**

state after a certain period of time. The system will remain in this state if no disturbances occur. However, disturbances are likely to occur due to the chaotic nature of the world, hence, the system will be forced into a **disturbed state** from time to time. Once the operator detects this disturbance, the **negotiation phase** initiates. In this phase, the operator has to determine if this disturbed state is something to worry about, or not. The operator does this by determining if its objectives are still being accomplished. If not, s/he has to determine if any countermeasures are required. And if so, the system will be configured to a **new configuration** such that the system will return to the steady state once again.

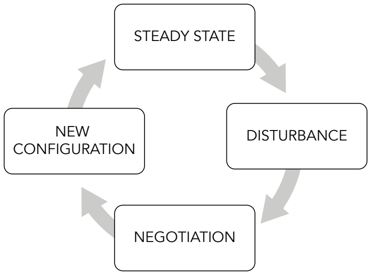


Figure 2.1: Four-step model to represent states of a controlled (human-machine) system.

This simple model can also be applied to the processes on the flight deck. The controller is in this case the pilot that has to detect disturbances, negotiates —with the flight deck systems, manuals, and other crew members— to determine a corrective action to reach a steady state. The controlled action can be or a combination of changing a system setting, altering the flight plan, communicating with the ATC and other traffic, or changing the objectives of the operator.

This model is simple; yet it provides sufficient explanatory power for this exploratory study. In the following, the main functions will be addressed to which this model can be applied to.

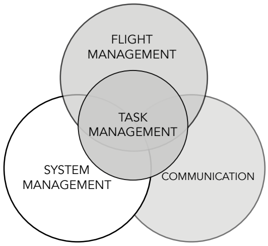
2.2.2. Functions on the Flight Deck

Different functional classifications have been proposed for the commercial flight deck (Abbott, 1993; McGuire et al., 1991). However, Abbott's functional categories are found to be the most comprehensive starting point and suits this study's explanatory purposes. Abbott (1993) defined that four main functions should be fulfilled by the human and flight-deck systems.

These four defined functional categories are, **flight management**, **system management**, **communication management**, and **task management** (see Figure 2.2). These categories expand on the traditional aviate, navigate, and communicate functions, which are taught since the earliest days of flight training. However, this traditional set is mainly used as a prioritization aid where the set of Abbott's functional categories embodies all functions on the flight deck.

The primary functions presented in Figure 2.2 have various sub or even sub-sub functions, which are closely related to the human information processing steps. These are for the sake of brevity not all discussed in detail. The more relevant functions for operational decision-making will be discussed below, starting with the flight management function.

2



Flight Management	Communication Management	Systems Management	Task Management
Flight Guidance Planning Monitoring Assessing Determining Actions Modifying Flight Control Planning Monitoring Assessing Determining actions Modifying	Receive Monitoring Acquiring Storing Processing Interpreting Evaluating Formulating Sending	Configuration planning Monitoring Assessing Comparing Diagnosing Determining Actions Modifying	Monitoring Scheduling Allocating

Figure 2.2: Functions and their relations of the flight deck as defined by Abbott (1993).

Flight Management

The primary function of an aircraft is the flight management function, where the others can be seen as supporting functions. The flight management function encapsulates two sub-functions namely, **flight guidance**, and **flight control**. Flight guidance can be considered as the strategic part of flight management and flight control as the tactical part. Both represent the aviate and navigate tasks.

The flight guidance function is the function in which the flight plan is defined, monitored, assessed, or modified. We will refer to this function also as the **flight-plan management** function. A large part of flight guidance is done pre-flight and starts with the choosing a destination airport. The plan should satisfy all requirements from the environment, regulations, and standard operating procedures. Once the objective and constraints are formulated, the path will be constructed by determining the lateral, vertical, and speed profiles. Most of this work is done by the dispatcher and is captured in the flight plan. This plan will be monitored in-flight by gathering all necessary information about the current state of the plane and the operating environment. This information is assessed to determine if the current state of the plane and environment is still according to plan (i.e., safely arriving on time at the planned destination). In case the objectives are not met, a corrective plan is created, and executed. Take for example a delayed flight, the corrective action would be to fly a bit faster (adjust the speed profile) to arrive on time at the destination.

Flight control is defined as the activity of adjusting or maintaining the flight path based on the requirements of the plan defined in the flight guidance function. This corresponds to the traditional view most people have of the pilot's task. For clarification, the planning part in this function is happening at a more tactical level compared to the flight guidance function and is only focussed on correcting the current state, or attitude of the plane, in order to follow the target path.

System Management

System management is the function in which aircraft systems are monitored and set to the desired state to fulfill the flight guidance objectives. Another objective of the system management function is to operate the systems within operating limits to prevent damage, or harm to the plane and passengers. This function can be seen as the enabler of the other functions.

A sub-function of system management is configuration planning. This type of planning entails defining a plan on how the system should be set in specific conditions. Often this is prepared beforehand and captured in checklists or procedures (e.g., switching fuel pumps off in case of an engine fire). It can occur that no procedure is available, and, in this case, the pilot has to determine the appropriate setting himself.

Task Management

Task management is the function that involves monitoring, scheduling, and allocating tasks. Task management is the overarching function that manages the processes of the other functions. In a sense, this function enables the state transitions of the other functions. The main objective in this function is prioritizing. But with the introduction of automation, it also serves the purpose of workload management. The pilot can offload tasks to automation such that s/he can focus on the most urgent tasks at hand. Hence, this function becomes increasingly important if tasks are dynamically allocated to automation, or to humans.

The functions on the flight deck act together to achieve goals in the world. All these functions interact with each other. For instance, a *new configuration* in a function can cause a *disturbance* within another function. Functions are also influenced by external factors. How all of these disruptions are handled will be discussed in the next section.

2.2.3. Managing In-flight Disruptions

Thomas (2003) studied the type of threats, or causes of possible disruptions, flight crews encounter in their daily operations. The most observed threat is caused by adverse weather (20.6% of all operations), followed by system malfunctions (14.4%), and operational pressure (11.5%). Less frequently observed threats are caused by traffic, ATC, airport conditions, terrain, ground handling, and passenger events. These factors are dynamic and have elements of uncertainty and are therefore difficult to plan for in advance of the flight. The pilot therefore needs to manage these disruptions in-flight.

As mentioned before, all the management functions can be expressed with the control loops presented in Figure 2.1. A combination of the identified functions and states are presented in Figure 2.3. Further, each control loop is presented along with their interactions. Challenges can be pinpointed by studying the processes and interactions during an in-flight disruption. Four types of disruptions will be explored to provide insight on the challenges on the flight deck.

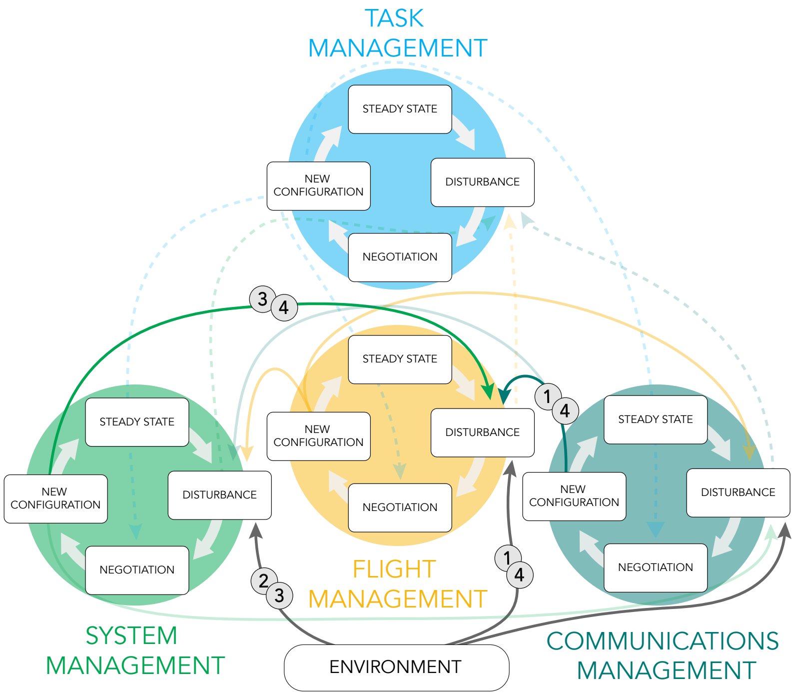


Figure 2.3: A model combining functions (as defined by Abbott (1993)) with processes (as presented in Figure 2.1) to highlight interactions used to explain the challenges during in-flight disruptions. The various types of disruptions are signified with numbers 1 to 4.

Type 1: Disruptions on the Flight Plan

This type of disruption is classified as a disruption that has a direct impact on the flight plan, and thus the flight management function. These disruptions are observed directly from the environment or are communicated to the flight crew via radio or other means. Environmental factors that cause such disruptions are for example, weather, operational pressure, traffic, ATC commands, airport conditions, terrain, and ground handling (Thomas, 2003). The pilot has to determine if the flight plan is still meeting the objectives, or whether a new plan is needed.

Once a new plan is constructed, consequential processes are initiated (e.g., systems are configured to meet the new plan). In case of a full holding pattern (environmental factor) a plan is constructed to fly slow and to save fuel. This causes a disturbance for the system management function and the throttle will be reduced to meet this more efficient airspeed. This type is expressed in Figure 2.3 with the number 1.

Type 2: Disruptions on the Systems

There are also factors from the environment that can cause a disturbance to systems, and thus the system management function. For example, a bird strike could cause a damage to a certain system. If this system that can be isolated and a redundant system can be used, there will be little to no impact on the remainder of the flight. The flight crew relies heavily on alerting systems and checklists during such events. This type is signified in Figure 2.3 with the number 2.

Type 3: Disruptions on the Systems Impacting the Flight Plan

This type of disruption is very similar to type 2, but in this case the *new configuration* from the system management function will cause an impact on the flight plan, and thus the flight management function. Sometimes a malfunction cannot be isolated, or no redundant systems are available. This can result into a loss off a certain capability. For example, a hydraulic leak can result into a reduced functionality of the flaps. It can be that the flaps cannot be extended further than halfway. If full flaps were planned for landing, then this will cause a disturbance on the flight plan and replanning becomes necessary. For example, a landing site needs with a longer runway needs to be selected if the currently planned runway is too short.

Counteracting this type of disturbance requires the crew to predict the consequences and understand the impacts of reduced capabilities. This type is annotated in Figure 2.3 with number 3.

Type 4: Disruptions on Both the System and the Flight Plan

Lastly, there is a combination of type 1 and 3. During such cases, both a system malfunction and environmental conditions impact the flight plan, for example during icing conditions and a malfunctioning anti-ice system.

2.2.4. Task Difficulties

Thus far, the process of handling disruptions has been elaborated. Based on this work, several difficulties that occur on the flight deck can be described. Difficulties arise in all of the previously introduced states: the *disturbance state*, *negotiation phase*, and *new configuration* state, which will be elaborated below.

Detecting Disturbances

Several cognitive challenges arise during the detection of flight-plan disturbances. One of them is that information about environmental factors needs to be obtained through many different sources. Weather, traffic, and airport conditions are all obtained with their own format and system. Information is spread out over a variety of manuals or supports. Not only the fact that information needs to be obtained from a variety of sources, also the volume of the information makes selecting the right information hard. Documentation is often very lengthy and environmental conditions are often presented unfiltered, not prioritized, and not context specific. Hence, finding the right information at the right time becomes a lengthy process.

Another complication occurs with the information found in Notice to Airmen (NOTAM)s and weather reports. This information essentially needs to be decoded by the pilots, for example by plotting it onto a map, before it can be used in assessing the effect of a disturbance.

Furthermore, the impact on the flight plan caused by a system state is not always obvious. Limitations of the systems are not always presented, nor fully understood (Reitsma et al., 2017). System knowledge or manuals are needed to fully understand the capabilities of the plane. For the pilot it is not always clear if certain operations are allowed or not (e.g., instrument landings).

To provide an example of this challenge, we can refer to the snow scenario presented earlier; the contaminated runway state was conveyed with a code at the end of the METeorological Aerodrome Report (METAR). On this specific day, this was presented with the code 'R36C/490693'. Obviously, this message is not straightforward and significant mental effort is needed to determine that runway 36 center is covered by 51% to 100% with a 6mm layer of dry snow. Resulting in a *medium* braking action. However, the crew in the snow-scenario was aided by the air traffic controller who notified them last minute that the most recent measured braking action was *medium to poor*. The decoding of the information was therefore done, but determining if this had an impact on a safe landing still needed to be done by the crew, and this was just too short notice to calculate the required landing distance while being on final.

Assessing Disturbances

Secondly, issues arise during the negotiation phase. Environmental conditions and systems states need to be transformed into flight-plan relevant information to determine if the flight plan is still satisfactory (e.g., if the plan is still safe or in-time). This can be done by asking the questions like when and where the systems are needed, specifically in the case of a disruption caused by systems (type 3). Basically, one has to combine the system capabilities and the environmental conditions with their flight plan to determine any issues for the remainder of the flight. Predicting and memorizing all consequences is challenging. This process is hard because it requires many in-between steps. Currently, estimating and predicting consequences is based on experience and good airmanship (Reitsma et al., 2017).

In the snow scenario, this transformation from braking action to landing performance was done with tables. This is a laborious process, if worked out into detail. As mentioned before, the process of assessing and integrating information into a flight plan demands a lot of cognitive effort and relies on the human memory, which is known to have its limitations. Under stress and concurrent tasks, distractions can cause unconsidered or forgotten impacts, which can have grave consequences.

Adjust the Plan

Once the impacts on the flight plan are obtained and found to be non-acceptable, the flight crew needs to determine a corrective action. Here again, the crew encounters the challenge of gathering all relevant and usable information.

If the crew from the snow scenario had decided to divert to another airport, they needed to find an airport within range, with good runway conditions, and preferably not too much traffic. This search for information is time consuming and only a few options can be considered. The crew is currently supported by dispatch to make such decisions. Often it takes a long time to fully check all conditions requiring time that is sometimes not available. Therefore, the crew has to balance between speed and thoroughness.

2.2.5. Conclusions

The previously discussed model of disruption types provides insight on how complex flight management can be. Accurate information in advance of the flight reduces the risk of unforeseen events and the need for in-flight replanning, but even with the best planning disturbances occur.

These disturbances can be challenging for pilots in many ways. Gathering and assessing flight-plan relevant information is challenging. Currently, the disturbances on the system (malfunctions) are managed quite well according to (Thomas, 2003). However, it remains challenging to understand the implications of a certain malfunction or disturbance on the flight plan (Reitsma et al., 2017). These are currently not presented in an easy-to-observe way. It is difficult to find out for pilot what the impacts are on the flight plan. Ironically, this is the main task of the pilot. Information about the current state of the environment and the system needs to be gathered, decoded, and assessed, all while flying. This process is unstructured and is performed based on pilots' incentive and experience.

It can therefore be argued that the pilot is better off with ready-to-use information. In other words, information should be provided in the format of the flight plan, for instance *"you will not overrun the runway, under the current condition X."* Hence, efforts for future flight-plan-management support enhancements should provide an easily accessible overview of the impacts on the flight plan and conditions in the world. Next, the extent to which the flight plan management function is supported by current flight deck systems will be examined.

2.3. Current Flight Deck Supports

The glass cockpit has been around for a while now, and with the introduction of the Electronic Flight Bag (EFB) the paperless cockpit became reality. Flight-crews have faster access to more information than ever before. But the question that remains is how does all this information support the flight crew in performing their task?

The main responsibility of the flight crew is the success of the operation and the well-being for the passengers and plane. A well-considered flight plan is crucial for successful operation. Hence, the flight plan management function is one of the primary functions that needs to be supported. Evaluating the flight constraints and implications on the flight plan is essential according to Harris (2007), but can be a taxing task especially under highly dynamic circumstances. This leaves us with the question, *"how are the modern flight decks presenting information to the flight crew to evaluate what can and cannot be done operationally?"*

Flight plan management is an information problem in which the flight crew has to combine information from various sources about the **operating environment**, and the **aircraft's systems**. Sequentially, the crew has to transform this information to determine, whether and if so, how the previously assumed flight constraints are affected, and what the consequences are for their operation. The interaction between the plane and environment is important since the threats to safe operations are not only caused by system malfunctions, but the majority of the threats are caused by effects from the world, like weather, traffic, terrain, ATC, and airport conditions (Thomas, 2003). These sources are highly dynamic and uncertain. Continuously updated information is needed to determine the implications on the flight plan.

The aim of this section is to compare flight deck architectures on how they present environmental disruptions, system malfunctions, and how they support flight plan management by combining environmental and system information to present impacts on the flight plan. First, information from the operating environment available on the flight deck is reviewed in Section 2.3.1. This is done holistically since various aircraft types have similar means to obtain this kind of information. Second, information about the system status is reviewed for five flight deck families in Section 2.3.2. A similar malfunction will be used to compare the various architectures.

2.3.1. Environmental Information Supports

The environment can impose disruptions from various sources, such as the airport and airspace infrastructure, terrain, weather, traffic, and air traffic control authorities. How this information is made available on the flight deck will be elaborated below.

Terminal / Route Information

Information about the airport facilities, standard procedures, and routes are published in the Aeronautical Information Publication (AIP) or Airport Facility Directory (AFD). Besides these publications, the crew has also an employer defined operations manual in which operational information can be found that the operator may deem necessary for the proper conduct of flight operations. This includes for example, preferred routes, Standard Operating Procedures (SOP)s, operating minima, escape routes, and minimum flight altitudes. Day-to-day information about the current conditions are communicated by NOTAMs, while short notice information is provided by ATC or the dispatcher.

Despite the recent change to an electronic format of these manuals and NOTAMs (see a & b in Figure 2.4), the content of information is similar to the paper version. One step towards integrating and transforming the content to a more operational format is done on Boeing's Airport Moving Map (AMM) and Airbus's On-Board Airport Navigation System (OANS) (see c & d in Figure 2.4), which show the location of runways, taxiways, and other airport features in relation to the aircraft position. Additionally, the status of the runways and taxiways is shown (e.g., closed taxiways and active runways). The crew can with these new supports clearly observe if the flight plan is crossing any constraints on the ground.

Terrain Information

Besides the charts and procedures published in the AIP, flight decks are equipped with terrain information provided by Enhanced Ground Proximity Warning System (EGPWS). These systems present terrain and alert if the predicted path is colliding with terrain.

The terrain information is integrated on the flight deck on the Navigation Display (ND) and/or on a Vertical Situation Display (VSD). The Synthetic Vision System (SVS) presents terrain constraints on the Primary Flight Display (PFD) in an integrated manner.

Weather Information

Weather is dynamic and can be difficult to predict accurately during the planning phase. Current weather conditions are distributed by Automatic Terminal Information Service (ATIS) or D-ATIS, which is the digital version of ATIS. Terminal Aerodrome Forecast (TAF)s, SIGnificant METeorological information (SIGMET)s, AIRmen's METeorological information (AIRMET)s, PIlot REPort (PIREP)s, forecasts, prognostic charts, wind/temp charts at different flight levels, are provided through the dispatcher and are often available in digital format. Furthermore, planes are equipped with weather radar that can detect real-time precipitation and turbulence. This information is readily available and integrated on the ND. Weather radar furthermore can alert for wind shears on the PFD and presents its location on the ND. Whereas the forecast needs to be requested and then processed mentally.

Traffic Information

Traffic is highly dynamic and to provide collision avoidance protection the Traffic Collision Avoidance System (TCAS) was developed. Predicted collisions are alerted on the PFD and ND. TCAS also provides a solution to avoid traffic, also known as a resolution advisory. However, only planes equipped with a transponder can be detected and avoided. With the introduction of ADS–B, traffic positions are made available and allow for airborne and ground traffic situation awareness, either displayed on the ND or EFB (see f in Figure 2.4).

ATC Clearances / Requests

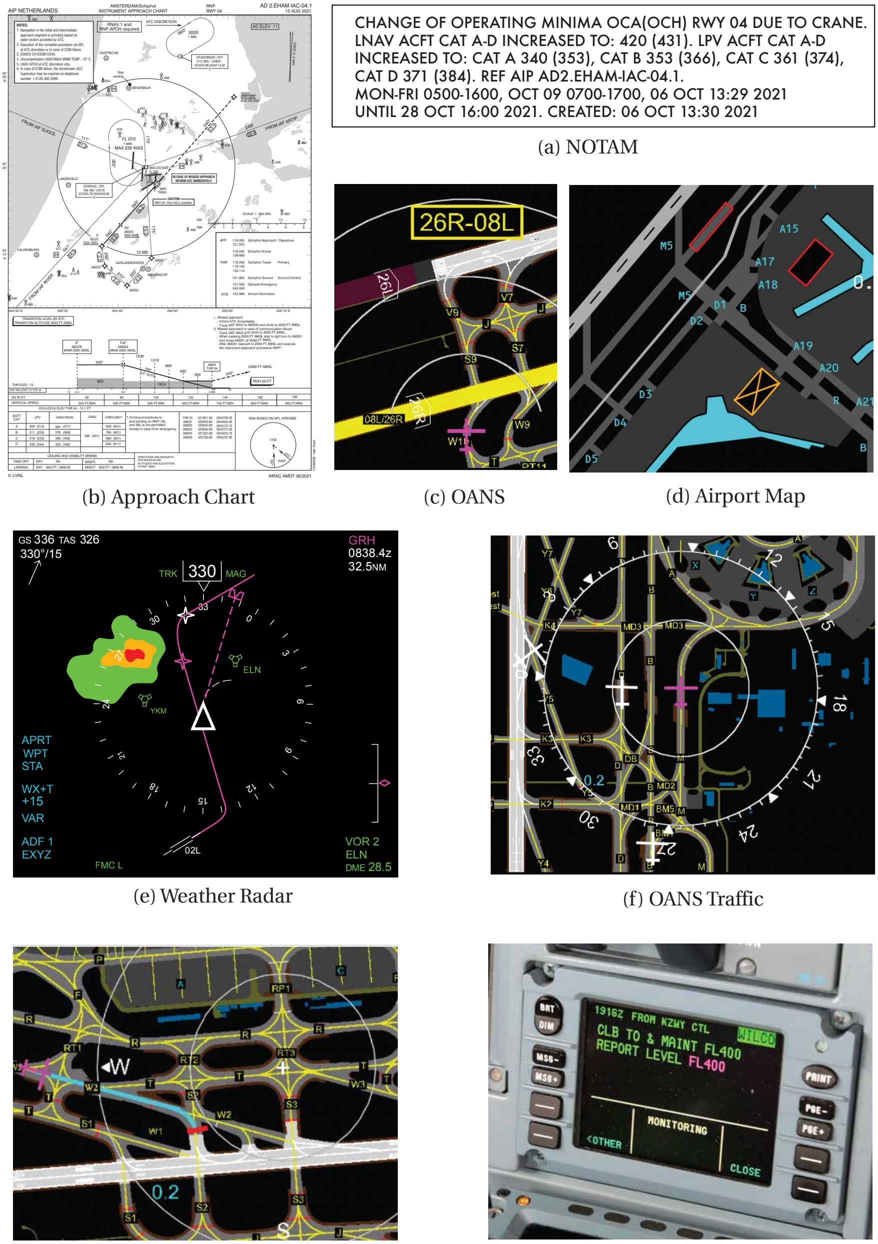
Obtaining information once airborne is possible due to communications. Communication is mostly done by voice (either through radio; either VHF, HF; or satellite), however with the introduction of datalink it became possible to send and receive information in an electronic format. Clearances and requests can be sent digitally with Controller Pilot Data Link Communication (CPDLC) (see h in Figure 2.4). This enables clearances to be uploaded to the FMS and thus to integrate these into the flight plan. Information can either be provided by ATC, for instance for clearances, or by the company, such as gate information. Clearances are integrated by On-Board Airport Navigation System (OANS) on the Airbus A350, by color coding a cleared and requested path, showing intentional constraints (see g in Figure 2.4), which is basically converting information into flight-plan-ready information.

2.3.2. System Implications

Besides the impacts caused by the operating environment the systems can impose also large disruptions on the flight plan. To illustrate this, five modern flight decks families are evaluated on how they represent information of the system status with respect to the intended plan. The Boeing 737 NG, Boeing 717/MD11 [1], Airbus A320/A330/A340,

[1] Both share a similar cockpit design called the Advanced Common Flight deck (ACF) and is shared with the Boeing 717, MD-10, and MD-11.

2



(a) NOTAM

(b) Approach Chart

(c) OANS

(d) Airport Map

(e) Weather Radar

(f) OANS Traffic

(g) ATC Clearances

(h) CPDLC

Figure 2.4: Examples of supports and information sources presenting the environmental disruptions. These figures are replicated or adapted from: b) https://eaip.lvnl.nl/, c), f), and g) Airbus (2011) courtesy Airbus, d) 787 FCOM courtesy the Boeing Company, h) http://www.pilotenbilder.de/blog/instrumente/7h-nur-wasser-mit-dem-airbus-330-nach-florida/

Boeing 777/787, and Airbus A380/A350.

A hydraulic reservoir failure on a single system will be used as a case study to show the differences in presenting system implications. Obviously, the impact of the failure on the aircraft status will be different on the various airplanes, but our interest is how and if operational implications are presented, starting with the most basic flight deck; the Boeing 737.

Boeing 737 NG

The Boeing 737 continuously evolved since it was introduced back in 1967. However, information presentation regarding the status of the engines and systems on the Boeing 737NG is however very similar to the classic 737. Dials are replicated in an electronic format, together with alerting block lights. The main alerting method relies on annunciator lights in front of the pilot together with corresponding lights on the overhead / pedestal panel. The crew has to scan the flight deck to determine what systems are causing the malfunction. Once the lights are identified, the crew will consult the QRH, either a paper or digital version, and look-up the corresponding alerting light. This will guide them through a non-normal checklist, which assists in reconfiguring the system to prevent and minimizing further deterioration of the plane systems. Once the failure is stabilized, the QRH provides the implications for the remainder of the flight. For the hydraulic system failure, various alert light across the flight deck will illuminate. After the reconfiguration of the systems, the crew is left with instructions and notes that are useful for the remainder or the flight, see b in Figure 2.5 for an example of this.

This is not only much information to interpret, but it is also not straightforward to determine what the exact effect is. The first step for the crew is to determine when an affected system will be used. Next, one has to determine if and how it impacts the intended operation. The landing distance for example needs to be checked with tables, which require additional information about the weather and runway conditions. As an example, take the note about the manual extension, see b in Figure 2.5. It requires considerable effort to figure out if a go-around and reaching the alternate field after lowering the gear is still possible. This is already a challenging task on the ground, needless to say that this is a difficult task once airborne.

Boeing 717 / MD 11

The Boeing 717 and MD11 share a similar flight deck, termed the advanced flight deck. The main system display is the Engine Alerting Display (EAD), which shows the engine status with an overview of all systems alerts. The Boeing 717 has also synoptic displays, which show the status of a particular system with alert related to the applicable system. Even though alert messages are presented in a centralized alphanumerical manner (see e in Figure 2.5), flight crews still depend on the assistance of the QRH, which is similar to what is available in the Boeing 737. An addition to the Boeing 737 is that the B717/MD11 also include a consequence page (see f in Figure 2.5) in which the alerts and consequence are summarized (Morgan & Miller, 1992). In the case of the hydraulic failure, the consequence page would include: “SPOILER INBD FAIL | REDUCED ROLL RATE AVAILABLE”. This is very similar to the notes from the QRH, only now in an electronic format.

2

Airbus A320 / A330 / A340

Airbus provide system alerting through the ECAM system. The status of the aircraft is automatically sensed and the appropriate actions to reconfigure the systems and prevent any further damage are shown. The completion of these actions is sensed and marked green when the system is in the correct state. After all actions are performed, a page appears with the limitations and inoperative systems (see h in Figure 2.5). This can be compared with deferred items, notes, inoperative systems, and consequence page. The A320/A330/A340 are also equipped with synoptic displays.

These indications tell the crew to check the landing distance and that they can do a CAT II approach with autoland. It is still up to the pilot to look up the landing distance in the tables and determine if an autoland with Cat II will be sufficient for their operation. Although this overview is quite clear, some items (the capability to retract the gear once lowered) is not provided and has to come from pilot's experience and system knowledge. Note that if such an implication is not considered by the flight crew, the consequences can have a major impact on the flight plan.

Boeing 777/787

EICAS, which was first introduced on the Boeing 757, is Boeing's main system status and alerting display. It shows alert messages in a centralized alphanumerical manner with an indication if a dedicated checklist exists. This checklist will appear in the ECL, which is like the QRH but has the functionality to sense if systems are in the correct position, like the ECAM system. The notes will be stored on a dedicated page. So, finding the checklists and storing the notes are easier with ECL. However, integration with the flight plan needs to be done by the flight crew (see c & d in Figure 2.5).

Airbus A380 / A350

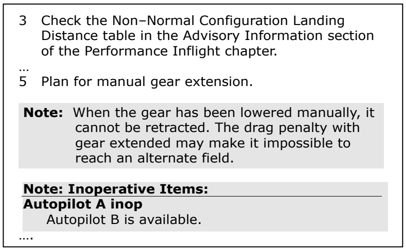
On the A350 and A380, the ECAM system is provided with more real estate provided by the larger displays. The inoperative systems are split-up into two categories, namely 'All phases' and 'Approach & Landing'. This makes it easier for the flight crew to determine in what flight phase the effects will limit the operation (see g in Figure 2.5). However, interpretation of much of the actual impact needs to come from the crew themselves.

2.3.3. Integrated System & Environmental Information Supports

ROPS & RAAS - The Airbus' Runway Overrun Prevention System (ROPS), and the Honeywell Runway Awareness and Advisory System (RAAS) are systems that integrate the aircraft configuration and status with the operational environment (e.g., runway conditions, weather) (Airbus, 2011; Clark & Trampus, 2011). They calculate the stopping distance required on a specific runway under various conditions. This is done in real time and considers changing conditions like wind. The system will alert if the runway is too short. This system off-loads the crew from making the calculation of the landing distance for the current configuration. The system makes the calculation eight times per second, faster that the crew can ever do. The system is providing the crew with essential information if a landing is possible yes or no. The brake-to-vacate function is another operational focused function, which can determine how to apply and configure the brakes to vacate the runway at an optimal taxiway (see i in Figure 2.5).

(a) Boeing 737

(c) Boeing 777/787



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

...

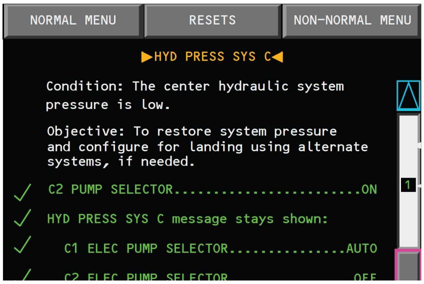
5 Plan for manual gear extension.

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.

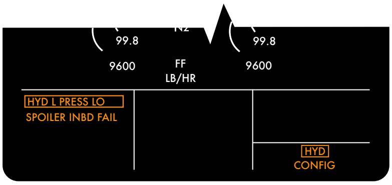
Note: Inoperative Items:
Autopilot A inop
Autopilot B is available.

....

(b) Boeing 737



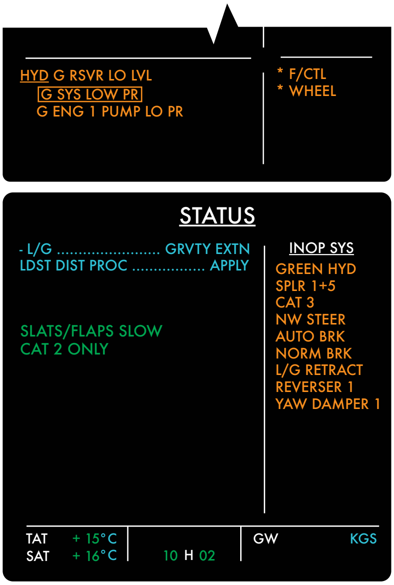
(d) Boeing 787



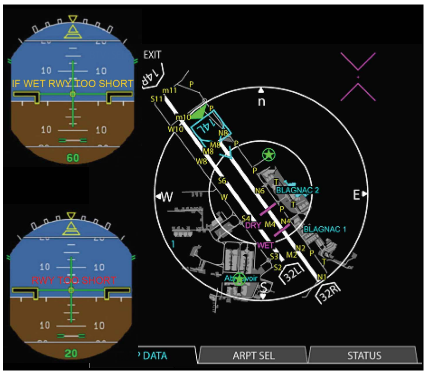
(e) Boeing 717 / MD11

(f) Boeing 717 / MD11

(g) Airbus A350/A380



(h) Airbus A320/A330/A340



(i) Airbus A350

Figure 2.5: Example of system management supports and how they convey implications on a flight plan for five aircraft architectures. These figures are replicated or adapted from: a) https://www.flaps2approach.com/journal/2014/3/14/boeing-737-ng-master-caution-system-six-packs-installed-and.html, b) Boeing (2007), d) 787 FCOM courtesy the Boeing Company, e) Morgan & Miller (1992), i), g) Airbus (2011) courtesy Airbus.

2.3.4. Discussion

From this case study, it can be observed that the accessibility of information is significantly improved by the introduction of electronic presentation. ECAM and ECL made it easier to obtain the required checklist. However, much of the content is similar to the paper version and the crew still has to combine all the limitations to determine when and what the effects are on the flight plan. This requires time, effort, and continuous attention, which are scarce in flight and during non-normal events. It can be observed that there is a trend in integrating information and provide operational alerting (e.g., TCAS, EGPWS, weather radar, airport map and ROPS/RAAS). These systems provide alerts in case collisions, or overruns are predicted. Alerts like, 'RUNWAY TOO SHORT', or 'NO TAKE OFF' are very clear in terms what operation cannot be performed. However, the support from these alerts and systems are limited to the tactical level. Finally, checklists provide guidance after a malfunction with notes, limitations and deferred items, but considerable effort needs to be spent by the crew to determine how events affect the operation (Australian Transport Safety Bureau, 2013). Therefore, system-wise the crew is relatively unsupported to fully comprehend and predict the repercussions of a change in system status.

2.3.5. Conclusions

A comparison of various flight decks reveals that more recently introduced flight decks and systems are integrating and transforming information into a more operational format. However, currently operational alerting is limited to support on a tactical level, but this could be expanded to combine more information for the entire flight plan, supporting the flight crew also on a strategical level. This will make it easier for pilots to obtain an overview what operations can and can't be done, which is beneficial during high-workload, complex and time-critical events. Systems that can assess the intended plan(s) based on up-to-date information have the potential to off-load the pilot, improve the quality of the assessment, reducing unconsidered effects and reducing the dependency on pilot's experience and expertise, which is favorable with reduced flight crew experience with non-normal events.

2.4. Options for Task Load Reduction

Up to this point, the challenges faced by pilots during day-to-day operations have been outlined, along with how current displays support the flight crew in understanding impacts from both the environment and the system. System management on the other hand seems like a potential candidate for increased automation (Bailey et al., 2017; Harris, 2007). Automating system management tasks will have the potential to lower pilot workload especially during non-normal events. It furthermore allows the crew to focus on what is really important (i.e., flying the plane and plan the remainder of the flight). The question is: 'How much can the pilot's task load be reduced?' The aim of this section is to get insight on how much the system management task can responsibly be automated. The preliminary quantification is essential before any design efforts are spent.

Bailey et al. (2017) describes that crews are benefiting from short checklists during abnormal events. If the pilot were relieved of all or the majority of reconfiguration steps in the procedures, the likelihood of devoting more attention to planning and executing a contingency plan would increase.

Not only will automatic system reconfiguration likely reduce workload. Increased automation has also the potential to resolve issues regarding incorrect execution of the checklist. Where the electronic checklist helped to solve checklist errors like skipping a checklist or omitting a checklist line item (Boorman, 2001), a fully automated re-configuring system may also eliminate or correct incorrect switching actions (e.g., selecting the bleed switch instead of a pack switch (Air Accidents Investigation Branch, 2011)).

No doubts exist whether the technology is ready to do automatic re-configuration of the system, since many system management tasks are already done automatically. Take for example, on the Boeing 737-800, automatic electrical-load shedding in case of electrical malfunctions, or automatic re-configuring of pack inflow during an air conditioning pack malfunction. However, some items cannot be practically and reliably sensed or performed by automation. Take for example closing doors, establish crew communications or looking out the window to check the wing. These items remain something that the human needs to do. But many of the items that are already controlled or sensed through systems seem perfect candidates to automate.

Automation on legacy planes was added through an evolutionary, technology-driven process. This resulted into a patchwork of automated systems which is far from ideal. A holistic approach towards automation is beneficial for clarity and simplicity for the operators. Therefore, this proposed automatic re-configuration system is targeted at future flight-decks where the holistic approach can be applied. But it would also be possible to retrofit all controls and selectors, maybe even only digitally. The most important feature of the retrofitted flight-deck is that selector positions need to correspond with what the automation did, such that no confusion can occur.

Within literature, many authors suggest that systems should become increasingly automated to lower workload (Bailey et al., 2017; Harris, 2007). But to date, no literature was found that provides a quantification of what the potential benefits could be. In other words, how much shorter could the checklists become if system management tasks were automated? As a starting point, this analysis is applied to a Boeing 737-800 (Boeing 737-86D) since this could be an aircraft suitable for single pilot operations due to the type of missions these planes fly. This study will also provide a break-down of the structure of a common Quick Reference Handbook (QRH) that can provide insight into the current available guidance material on the flight-deck. Deviations due to additionally equipped systems are considered small and not altering the result too much compared to other 737.

2.4.1. Method

As mentioned earlier, the question is no longer if system reconfiguration steps *can* be automated but rather if they *should* be automated. The possibilities seem endless; however, past experience has shown that the introduction of automation can lead to skill degradation and out-of-the-loop situations (Bainbridge, 1983). Designers should carefully reconsider what to automate and how to do this appropriately without introducing potential problems. Since the QRH contains steps for all tasks, it is necessary to determine which tasks should be automated and, in particular, which should not.

Assumed Pilot's Role

As learnt from the past, humans are poor monitors, not good in routine tasks, nor memorizing (Fitts, 1951; Harris, 2007). But humans can be creative and can act on their intuition. On the other hand, automation is not good at dealing with events for which it is not programmed. Today the pilot is a flight path controller, systems monitor, and flight deck manager. In this section, a shift in the role of the pilot is envisioned. The pilot would be more involved and focused on flying and flight plan management. Planning often requires a knowledge base, intuition and creativity, something that is difficult to capture in a system. Finding a suitable path and environment for the jeopardized systems is something that the human is good at since it requires intuition and creativity. The pilot is released from the task of troubleshooting (i.e., diagnosing, monitoring, and re-configuring the system, which are all routine and well-defined tasks).

Systems on modern planes have become very complex. Understanding and diagnosing the entire system to a deep technical level is almost impossible. Especially under high workload and stressful situations. The system has better accessibility to relevant system information and is also more accurate in interpreting these data. Furthermore, in response to system failures the pilot is expected to follow the prescribed procedure, almost like a machine. This eliminates the pilot strengths of being creative or intuitive. The question is: why is the pilot required to perform this task in the first place? On modern planes many systems have redundant components. Malfunctions can often be contained by switching on the redundant system and flight safety is rarely endangered. However, the contained but inoperative systems can impose limitations to the remainder of the flight, which can have grave consequences if the pilot is unaware. Hence, these items cannot be left out.

Automation Candidates

In line with the previously discussed pilot's role as a flight path manager, some items that can technically be automated are deliberately chosen not to be automated. These items include actions that are impacting flight characteristics significantly. Why? Well, this has all to do with keeping the pilot engaged. Pilots fulfill a role as a back-up. Once the autopilot cannot cope with the situation, the pilot has to take over. Being aware of the basic configuration the plane is crucial to keep the pilot in-the-loop. These basic configuration items include thrust settings, gear levers, flaps setting, speed-brakes and trim settings. These items are not suitable to be automated.

Reconfiguration steps that handle resource systems such as, hydraulics, electrical, fuel and pneumatic systems, are good candidates to be handled automatically. This is because these systems are often redundant, the systems are already monitored by the plane, clear limitations exist, and the procedures are also clearly defined.

Plane and passenger health protection systems are also suitable candidates. Often these tasks are time critical, the corrective action is well defined, and the systems are also equipped with sensors. Furthermore, options for resolution are often limited.

To generalize, the described tasks above are tasks that have the main objective to (1) protect the plane and passengers from harm, or (2) provide comfort, or (3) maximize the performance of the systems on-board the plane. If checklist items serve one or more of these goals, then they are often good candidates for automation.

Figure 2.6a shows that many of the steps belong to this category. Checklist items 1, 2, 3, and 4 are all candidates to be automated. This is also true in another example, shown in Figure 2.6b. Items 1, 2, 3 and 4 can be automated. However, item 4 requires some context. Ice can be expected below 40,000ft, in clouds and if the outside air temperature is below or near the freezing point. To determine this, some integration of the systems is required. Furthermore, it can be linked to SIGMETs that report or predict icing conditions.

Figures 2.6a and 2.6b show clear actions. These are presented with the selector on the left-hand side, dots in the middle and a target state on the right. The example checklists show also choose items decision statements. In this case, the pilot has to decide what condition applies. These items are often already auto sensed, on planes that are equipped with electric checklists. They are relatively easy to automate since these options often describe if a light is illuminated or extinguished, which are already sensed by the system.

WING-BODY OVERHEAT | **WING-BODY OVERHEAT**

Condition: An overheat from a bleed duct leak occurs.

Objective: To isolate the bleed duct leak.

1 ISOLATION VALVE switch. . . . . CLOSE

2 Choose one:

◆**Both** WING-BODY OVERHEAT lights illuminated:

TRIM AIR switch . . . . OFF

Note: Passenger cabin temperature control may be less accurate.

■ ■ ■ ■

◆**Only right** WING-BODY OVERHEAT light illuminated:

►►**Go to step 3**

◆**Only left** WING-BODY OVERHEAT light illuminated:

►►**Go to step 8**

3 R PACK switch . . . . OFF

This causes the operating pack to regulate to high flow in flight with the flaps up.

4 BLEED 2 air switch . . . . OFF

▼ Continued on next page ▼

(a) Checklist containing actions, decision items, notes and remarks on the to-be-expected system behavior.

BLEED TRIP OFF | **BLEED TRIP OFF**

Condition: One or more of these occur:
•An engine bleed air overheat
•An engine bleed air overpressure.

1 WING ANTI-ICE switch . . . . OFF

2 TRIP RESET switch . . . . Push

The BLEED TRIP OFF light extinguishes if the bleed air temperature has cooled below limits.

3 Choose one:

◆BLEED TRIP OFF light **stays illuminated**:

PACK switch (affected side). . . . . OFF

This causes the operating pack to regulate to high flow in flight with flaps up.

Avoid icing conditions where wing anti-ice is needed.

■ ■ ■ ■

◆BLEED TRIP OFF light **extinguishes**:

►►**Go to step 4**

4 WING ANTI-ICE switch . . . . .As needed

Caution! Use of wing anti-ice above approximately FL350 may cause bleed trip off and possible loss of cabin pressure.

■ ■ ■ ■

(b) Another checklist containing actions, which have context specific target states and remarks that are important for the remainder of the flight.

Figure 2.6: Example checklists extracted for a Quick Reference Manual (QRH) of a Boeing 737-800, as presented in (Boeing, 2007).

Conditional statements along with objective statements presented on top of the checklist, in a grey box (see Figure 2.6a and 2.6a), are no actions and therefore out of the consideration to be automated. This also holds for operational notes and informative statements, describing the expected behavior of the systems after the action is performed.
To summarize, the items that are selected to be suitable candidates for automation in this study are as follows:

- Actions that have the primary function to protect the plane and passengers from harm, or maximize the functionality of the plane. These actions do not directly impact flight characteristics.
- Decision statements that can be measured with sensors.

With these criteria, each item in the QRH is being rated if they would be suitable candidates for automation. Firstly, all items in the QRH are categorized into actions, notes or remarks, decision statement, and conditional statements, which describe for what situation the checklist can be used. These items are then sequentially categorized into 'automatic', 'manual', 'informative', 'wait-until' or 'go-to-next-checklist' items. Wait items are, as the name suggests, items that describe to wait a certain duration or until a certain event occurred. An example of such items is 'wait for 2 minutes' or 'wait until the light has extinguished'. Some actions are not necessarily straight forward actions, sometimes they are more of an informative nature for operational purposes, for example 'continue normal operations'. Therefore, these are marked as informative statements, providing information for the remainder of the flight.

2.4.2. Results

In total 159 checklists are analyzed, both normal and non-normal including the (short) deferred checklists and items. All these checklists contain to a total of 1626 items. Of all the 1626 items, 68% is classified as an action, 13% as a condition that needs to be verified (choose item or decision statement), 10% as a conditional statement (items presented on top of the checklist) and finally 9% of the items are notes or remarks. This result is presented in Table 2.1.

Table 2.1: Checklist item step break down of 10 normal checklist, 12 deferred checklist/procedures and 137 non-normal checklists

Step Classification	Action Item	Decision item	Conditional statement	Notes & Remark	Total
Automatable items	411	175	-	-	586 (36%)
Informative items	244	-	164	138	546 (34%)
Manual items	405	34	-	5	444 (27%)
Go to ... item	40	-	-	-	40 (2%)
Wait items	10	-	-	-	10 (1%)
Total	1,110 (68%)	209 (13%)	164 (10%)	143 (9%)	1,626 (100%)

From Table 2.1, it can obtain that 36% of all items can be automated. The wait items are also potential candidates for automation since they require only a timer. Items that state to go to a follow-up checklists are also good candidates to be automated. Adding these items reveals that 39% of the tasks in the QRH could be automated. Leaving the pilot to read and execute 61% of items presented in the QRH.

Some notes and remarks are presented just below an action to provide some information about the expected system behavior. These items can become redundant if the automation is handling these items. This means that the number of informative items for the proposed automated system will be reduced as well. However, a critical assessment is required to determine if these items are superfluous. This information is often added, it seems, to prevent surprises, distinguishing normal from non-normal system behavior and increase trust in the system.

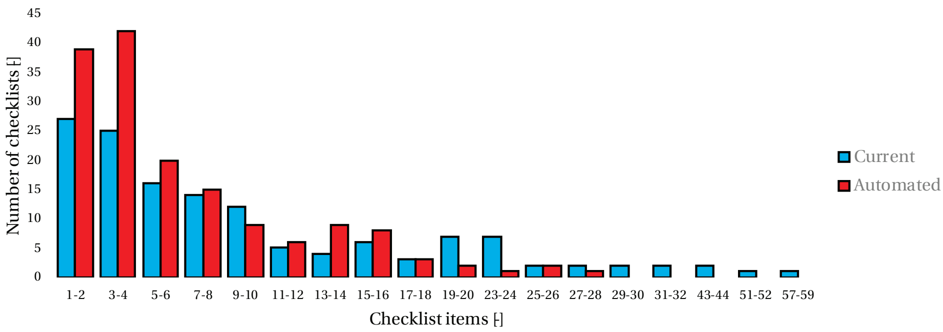


Figure 2.7: Occurrences of the number of items per checklist. Note the shift towards the left for the automated checklist concept.

In Figure 2.7, the amount of occurrences of the same number of items per checklists are presented. What is interesting, but not surprising, is that for the automated checklists, the number of checklist items is reduced. The extreme long checklists with >30 items are mitigated. The average checklist size is reduced to 4 for the automated checklist, compared to 6.5 items for the current system.

For the automatic checklist, the remaining items are for 55% informative and 45% manual action items. The checklist includes mainly items directly related to flying, flight plan management, or communication.

2.4.3. Discussion

The question remains if this result is sufficient to proceed with the development of such automation. This decision depends mainly on investments of modification, maintainability or development of these systems and expected cost savings, of for example RCO, or expected increase of level of safety.

Modifications to the Aircraft

The automation would require major adjustments of the systems. The system would require integration of sensed data, and a structured way of dealing with data. All this is technologically within reach. Most modern aircraft architectures have a internal network for data access across the plane. This new automation can tap on to this network. However, it would be easier to implement this on newly designed planes rather than retrofitting planes.

Need for Information Integration

One of the challenges is to provide context from outside the plane into this automated assistant. But again, this is not impossible, since modern-day cars are already equipped with, for example, speed limit indication, based on their current location. This would also be possible in aviation.

Controls and Switches

Although items are being automated, the pilot should still be able to control the items in cases of unexpected events. The question however is, do these controls and switches need to be as present as they are today. Since they are not used as much as before, maybe sporadically, they could be presented digitally on displays and/or integrated in a synoptic view, leveraging on touchscreen technology.

Saving Items does not Correlate to Time Saving

Although the results show that checklists can be shortened by letting automation perform many of the items, this does not directly translate into similar results of time saved. To estimate the time saved by automation, it is necessary to measure the duration required to execute each item. This can either be done physically or estimated with for example the well-known Fitt's Law. Furthermore, items with much text, like operational notes, take much more time than shorter action text items. The time to read these items can be estimated with for example an average reading speed ranging from 175 to 300 words per minute (Brysbaert, 2019). This analysis is quite labor intensive.

Also, the checklists are structured as troubleshooting trees. Based on the decision along throughout the process, the checklist will be longer or shorter. To investigate this properly, one has to determine all possible combinations of the decisions made while troubleshooting. This will provide a more accurate number for real life operations.

This study was intended to obtain an initial quantification of the potential candidates for automation on board commercial aircraft, which seem promising. Next would be to determine the time spent per item and checklist.

Legacy Aircraft

The Boeing 737 was introduced in 1967, and since then it went through many modifications and adjustments. This plane has some automation but does not incorporate the level of integration the most modern jets have. The QRH of the Boeing 777 and 787 is more compact, more structured. The ECL automated already many items (i.e., the decision items). Therefore, the benefits of implementing more automation on these planes is less compared to a less integrated plane like the Boeing 737.

2.4.4. Conclusions

This exploratory study provides promising results in the journey to develop a flight-deck with lower workload. Almost 39% of all checklist items are possible candidates to be automated. This result was obtained with the assumption that the pilot's role will be more focused on flying and flight plan management. Checklist items directly related to flying are deliberately not automated to keep the pilot in the loop. The average checklist size is decreased from 6.5 to 4 for the baseline and automated concept, respectively. This does not entail that 39% of the time is saved. Although, the reduction in terms of checklist items is significant. Planes require integration of information to make this automation possible. Even the most modern planes, that are equipped with electronic checklist which can sense the state of the system, can benefit from this concept. This is because the automation will not only perform decision items automatically but also executes them and taking the automation to the next level. In all cases it will likely reduce workload.

2.5. Preliminary Findings

This chapter provided us with a few key insights that can be used in our exploration for supports with elevated levels of automation.

The difficulty of the flight plan management task is to transform disturbances introduced by systems and the environment into impacts on the flight plan. Currently, no clear nor structured overview exist with the impacts on the flight plan. Presenting alerts based on impacts on the flight plan has the potential to reduce the cognitive load on the flight crew of translating the system and environment states into repercussions on the flight operation. These alerts should present impacts on a higher functional level, namely, the flight-plan level. Aircraft capabilities and the environmental conditions need to be combined to alert on *where* and *when* in the operation hazards are predicted. These types of alerts can be referred to as operational alerts.

Predicting how non-normal conditions affecting the flight plan depends currently much on the human. However, a trend towards improved supports, which integrate information from the environment and the system capability, has been identified, especially for ground operations support systems. Hence, the design approach of this project is expanding on the developments in industry.

Furthermore, the preliminary quantification showed that if system management tasks would be automated 39% of the actions required by checklists could be saved. Items related to flight-path management and flight control are chosen not to be automated to keep the pilot engaged during these tasks. Other items remained manual are the items that require visual inspection or could simply not be done by the automation.

Based on this, the necessary information for effective operational decision-making can be identified, along with tasks that may be 'safely'automated.

References

Abbott, T. S. (1993). *NASA-TM-109005 Functional categories for future flight deck designs.* Technical report, NASA Langley, Hampton, Virginia.

Air Accidents Investigation Branch (2011). *Air Accident Monthly Bulletin.* Technical report, AAIB.

Airbus (2011). *Flight Deck and Systems Briefing for Pilots A350-900 Flight Deck and Systems Briefing for Pilots.* Technical Report 02, Airbus.

Australian Transport Safety Bureau (2013). *In-flight uncontained engine failure A380-842, VH-OQA.* Technical Report AO-2010-089, Australian Transport Safety Bureau, Canberra.

Bailey, R. E., Kramer, L. J., Kennedy, K. D., Stephens, C. L., & Etherington, T. J. (2017). An assessment of reduced crew and single pilot operations in commercial transport aircraft operations. In *AIAA/IEEE Digital Avionics Systems Conference - Proceedings.*

Bainbridge, L. (1983). Ironies of automation. *Automatica*, 19(6), 775–779.

Boeing (2007). *Boeing 737-800 Quick Reference Handbook.*

Boorman, D. (2001). Safety benefits of electronic checklists: An analysis of commercial transport accidents. In *Proceedings of the 11th International Symposium on Aviation Psychology* (pp. 5–8). Columbus.

Brysbaert, M. (2019). How many words do we read per minute? A review and meta analysis of reading rate. *Journal of Memory and Language*, 109.

Clark, S. & Trampus, G. (2011). Improving Runway Safety with Flight Deck Enhancements. *AERO Boeing.*

Fitts, P. (1951). *Human engineering for an effective air-navigation and traffic-control system.* Technical report, Ohio State University Research Foundation.

Harris, D. (2007). A human-centred design agenda for the development of single crew operated commercial aircraft. *Aircraft Engineering and Aerospace Technology*, 79(5), 518–526.

McGuire, J. C., Zich, J. A., Goins, R. T., Erickson, J. B., Dwyer, J. P., Cody, W. J., & Rouse, W. B. (1991). *An Exploration of Function Analysis and Function Allocation in the Commercial Flight Domain.* Technical Report NASA Contractor Report 4374, NASA Langley Research Center.

Morgan, J. & Miller, J. (1992). MD-11 Electronic Instrument System.

Reitsma, J., Fucke, L., Borst, C., & van Paassen, M. (2017). Taking a Closer Look at Flight Crew Handling of Complex Failures – Ten Case Studies. In *19th International Symposium on Aviation Psychology (ISAP 2017)* Dayton.

Thomas, M. J. W. (2003). Improving organisational safety through the integrated evaluation of operational and training performance : an adaptation of the Line Operations Safety Audit (LOSA) methodology . *Human Factors and Aerospace Safety*, 3(1), 25–45.

3

Design and Evaluation of an Automated System Management Support

What is the impact on human performance if system management would be increasingly automated?

As was pointed out before, Reduced-Crew Operations (RCO) requires increased automated assistance to lower workload, in particular during abnormal events. A set of design requirements for the automated system management assistance was outlined in the previous chapter. Although the current level of automation of the system management supports is high, this level can be further elevated to reduce workload. However, a balance needs to be found to avoid adverse effects, such as reduced situation awareness.

This chapter presents an electronic checklist system with elevated levels of automation. First, the design will be motivated. After which, the results will be presented of a full human-in-the-loop experimental evaluation with this automated electronic checklist. The evaluation indicates whether workload is reduced and identifies any negative effects on situation awareness and decision-making.

Parts of this chapter have been published in:

Linskens, C.E, Reitsma, J.P, Borst, C, van Paassen, M.M, and Mulder, M. A Novel Automated Electronic Checklist for Non-Normal Event Resolution Tasks. AIAA SciTech 2021 Forum. January 2021.

3.1. Introduction

A Non-Normal Checklist (NNC) provides system and operational information to the pilot, and most important, step-by-step instructions to configure the flight deck to isolate deteriorating systems, restore system functionality, and therefore avoid hazardous situations. Many of these checklist steps require the pilot to move switches and selectors, which in Electronic Checklist (ECL) equipped aircraft are tied to sensors. When the effects of the pilot's actions can be detected by the system, these checklist items are called sensible checklist steps, or closed-loop line items. Closed-loop line items make excellent automation candidates since the level of automation is already high. The benefits of automated checklist steps are discussed in the following.

3

Most important, automating closed-loop-line items is predicted to lower the required mental and physical effort, and consequently free cognitive resources such that the pilot can focus on resolving the non-normal event, or on other competing tasks. Second, no attention shifting between different panels is required (e.g., the overhead panel and the main displays). Next, the displayed checklists can become shorter (i.e., the automated lines do not necessarily have to be shown). And finally, the automation has the potential to complete such tasks faster than humans.

Therefore, integrating automation in the process of checklist completion would allow the ECL to assist the pilot to lower time pressure, spikes in workload, stress, and problem-solving needs during non-normal situations (Burian & Barshi, 2003; Burian et al., 2005) and perhaps already set a next step towards realizing Single-Pilot Operations (SPO).

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 research question of this chapter is: *how does the proposed Automated Electronic Checklist (AECL) design compare against the state-of-the-art ECL in terms of workload, time requirements, and situation awareness during non-normal events?* The workload during these non-normal events is expected to decrease due to the reduced task load (i.e., one confirm action versus multiple buttons presses and switching actions). However, as Endsley et al. (2003) and Endsley & Kaber (1999) described, it can be expected that reducing the involvement of the operator will reduce situation awareness. Specifically, the perception and comprehension of the current state.

This chapter proposes automation to be applied to checklist execution. Thomas (2011) explored the appropriate Level of Automation (LOA) to automate a set of checklist 'memory items'. Comparable approaches have been explored in other studies. For example, only showing the current step (Li et al., 2017), similar to Electronic Centralized Aircraft Monitor (ECAM), or reducing checklist length by showing the information through synoptics (Etherington et al., 2020). However, no other study evaluated the impact on human performance if the pilot would be relieved from the checklist execution task, and the presented checklist steps would be removed, as they have become the automation's responsibility.

In this study, the proposed (automated) prototype is compared against a reproduced Boeing 787 ECL in a human-in-the-loop experiment wherein fourteen 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 displays[1] and alerting system. In a between-participants design, each participant was assigned one of the ECL displays (ECL or AECL) to conduct both scenarios and results were evaluated in terms of time requirements, experienced workload, situation awareness, decision-making, managing a secondary task, and their design acceptance. Potential automation drawbacks such as complacency, automation bias, and skill degradation (Bainbridge, 1983) could not investigated in-depth in this research since these are often long-term effects.

3.2. A Proposed Automated ECL

Implementing an automated solution for handling checklists requires answers to the questions of what task to automate, to what extent, and when. Tasks can be categorized under four stages, (1) information acquisition, (2) information analysis, (3) decision and action selection, and (4) action implementation (Parasuraman et al., 2000). By using this classification, the level of automation of the current ECL can be quantified, and the LOA of the proposed design can be determined.

3.2.1. Current Level of Automation of the ECL

ECLs already adopt high LOAs within the first three stages. Acquiring information is already automated, where possible, as the aircraft can detect malfunctions without the intervention of the pilot. Further, information analysis is also automated since the aircraft can integrate information input into a single or multiple Engine Indicating and Crew Alerting System (EICAS) messages with the associated checklists displayed on the ECL. Decision and action selection is provided through predefined checklists that prescribe the correct configuration and provide supplementary information along with flight continuation advice (e.g., divert to the nearest suitable airport, avoid icing conditions, or limit the flight altitude). Note that, although it is generally advised against, pilots do have authority to override checklist steps and organize the checklist order at their priority.

In contrast to the previously mentioned stages, the action implementation – the execution of the checklist steps – is still completely manual, but it should be noted that the pilot's actions are supervised by the aircraft through autosensing (i.e., the closed-loop line items).

3.2.2. Selecting Automatable Checklist Items

The proposed design is focused on automating the action-implementation class, but up to what point? Establishing an appropriate LOA is vital since different levels are found to affect performance, workload, and situation awareness. Therefore, the gains and drawbacks of automating certain checklist steps are evaluated based on automatability, situation awareness, time requirements, and authority of the pilot. From this, the appropriate LOA of each checklist step can be determined.

[1]all operable by touch

Automatability

Firstly, the automatability of checklist steps is assessed. Open-loop line items, 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 recognized on the ECL by the grey box in front of a step (see Figure 3.1). Furthermore, conditions, objectives, and operational notes do not hold a status of completion. Instead, they exclusively provide information. As such, there is nothing to complete and no possibility for automation. Deferred-line items refer to a Normal Checklist (NC) affected by a completed Non-Normal Checklist (NNC). For example, a deferred-line item may describe a change of a 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 is only relevant just before approach. In this study, NCs are not (yet) considered for automation due to the limited simulation duration.

Closed-loop line items are auto-sensed by the aircraft and, when assuming the aircraft would be capable of moving switches and selectors, have the potential to be automated. Even though the assumption is made that such steps are automatable, the different types of closed-loop line items were assessed if they *should* be automated.

Situation Awareness & Authority Requirements

The need for building situation awareness is already integrated within some of the checklist steps since they inherently differ in authority. Instructions for certain steps may indicate 'Confirm', which requires a verbal agreement of both pilots before action is taken (Boeing, 2007). Such steps, due to their respective impact, are classified as higher authority. They include, for example, engine thrust lever, an engine start lever, an engine, and a generator drive disconnect switch. 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 irreversible steps, which, when effectuated, are permanent and can only be reinstalled through servicing by maintenance. Consequently, any step of higher authority, which needs confirmation of both pilots, is excluded from automated execution, to keep the human involved in high-impact or irreversible control actions.

Time Requirements

Some steps are time-consuming, such as calculations and timer steps. These time-consuming steps are likely candidates for automation. Extensive calculations are typically triggered by non-normal events that 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 use dedicated landing tables in the Quick Reference Handbook (QRH) to estimate the aircraft's landing distance. Such calculations are automatically performed in the proposed design (AECL), which displays the output and output-yielding inputs (see Figure 3.1 for an example).

Timer steps ask the pilot to wait for a certain amount of time (generally a few minutes). Manual execution of such steps increases the risk that pilots do not return to a

Table 3.1: Overview of what is automated and integrated in the dropdown menu by NNC step type

Step Type	Automated?	Dropdown Menu?
Condition, Objective, and Operational Note	No	Yes
Closed Loop Line Item (i.e., Auto-sensed Action)	Yes	No
Open Loop Line Item	No	Yes
Higher Authority Line Items (Confirm Line Item, Guarded Switch, Irreversible Action)	No	Yes
Timer & Calculation Line Item	Yes	No
Closed Loop Conditional Line Item	Yes	No
Deferred Line Item	No	No

procedure to finish it or introduces time consuming wait periods. Such steps 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.

Automation Overview

An overview of all checklist-step types, and whether they are automated, is presented in Table 3.1. In this first attempt the LOA of the AECL is kept low, since adverse effects will be amplified with higher levels of automation (Endsley et al., 2003) (e.g., out-of-the-loop syndrome). Automation is initiated at the pilot's discretion (i.e., the automation will execute the task only if commanded by the pilot). Beyond the initiation stage, autonomy is higher since automation will continue until finished, unless otherwise instructed by the human operator. The pilot therefore continues to have full authority over the system.

3.2.3. The Dropdown Menu

The proposed design also includes the option that the pilot can always check the steps of the automation, or even complete the checklist manually. Within the non-normal menu, checklists can be expanded, and collapsed by pressing the right-side arrow button (see Figure 3.1). The expandable checklist is referred to as the dropdown menu and it consists of two main domains: the checklist content, and a row from which automation and checklist progress is handled (see Figure 3.1). 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 in the dropdown menu as they either present useful information or require pilot input in order to be completed. The dropdown menu excludes any steps performed by the automation and other information related to the automated execution which is, therefore, non-relevant 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.

To avoid displaying non-relevant information, the AECL dropdown menu dynam-

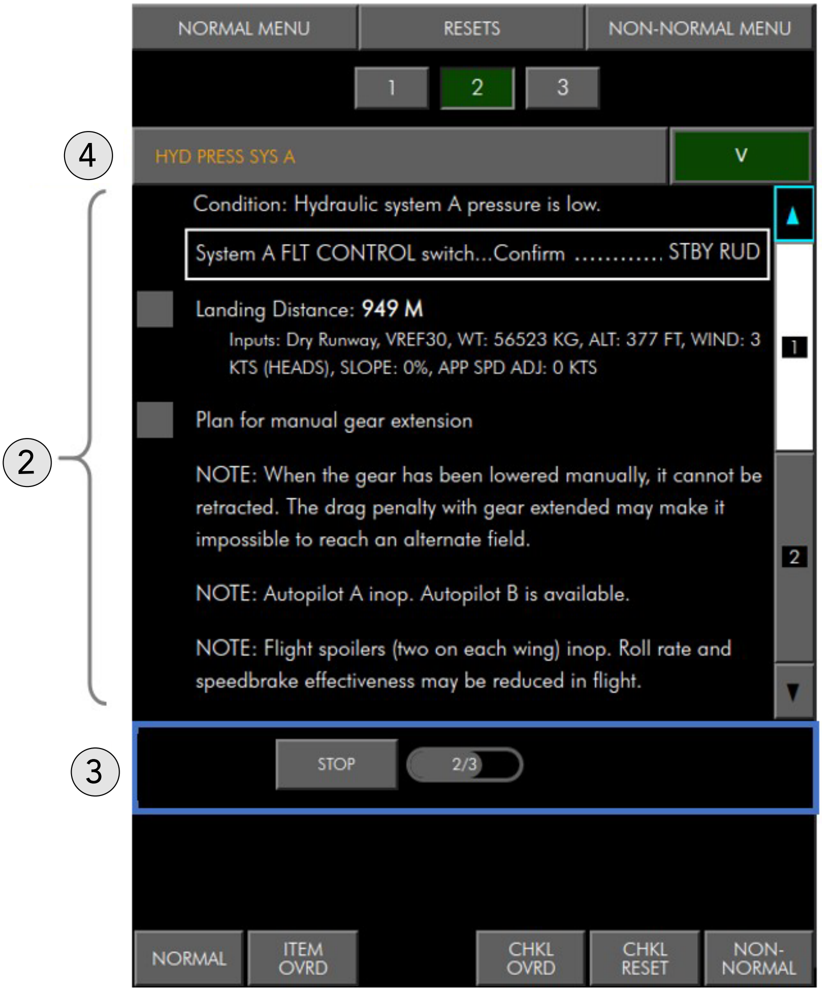


Figure 3.1: By pressing the arrow on the right-hand side **(1)**, the dropdown menu can be opened and closed. The dropdown menu itself consists of the reduced checklist content **(2)** and a row from which automation and checklist progress is controlled and supervised **(3)**. When deemed necessary, the complete checklist can be accessed by pressing the checklist name **(4)**, alike on the Boeing 787 ECL

ically updates when necessary after completing a conditional line item (an example is shown in Figure 3.2). 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 complete checklist may be desired to gain further context (see Figure 3.1). One example is reviewing 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 3.1.

3.2.4. AECL Concept

Whenever a checklist contains automatable steps, the automation button can be pressed on the left to commence the automation (see Figure 3.2a). With automation in progress, the operator has the possibility to stop the automation. The progress of the automation is presented with an automation progress bar, which reports the fraction of the steps completed through automation divided by the total number of automatable steps (see Figure 3.2b). Once completed, the progress bar displays 'Done', as shown in Figure 3.2c. Additionally, from Figure 3.2c, 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 3.3a for reference). After completing the remaining steps, the checklist displays its status of completion through the green bar stating 'Checklist Complete' (see Figure 3.3b). Additionally, as shown in Figure 3.3c, the clear button on the right appears by which the operator can eliminate the checklist from the non-normal menu.

3.3. Experiment Design

The objective of the 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 ECL and EICAS.

3.3.1. Participants

In total, fourteen participants volunteered to take part in the experiment. Due to the specific system knowledge requirements of the experiment, the participants are, or were (recently retired), all professional airline pilots with a Boeing 737 type-rating. The participants were divided into two groups, the first group completed the entire experiment with the baseline ECL and the second group was presented with the AECL. The average Boeing 737 flight hours of the participants in the baseline group was 10,150 hours, compared to 6,800 hours in the AECL group. The average age for the baseline group was 44, and for the AECL group this was 35. The baseline group consisted of 4 Captains and 2 First Officers whereas the AECL group consisted of 2 Captains and 4 First Officers. The difference was caused by the late enrollment of the participants and the limited number of participants. However, the groups are comparable enough for this exploratory study.

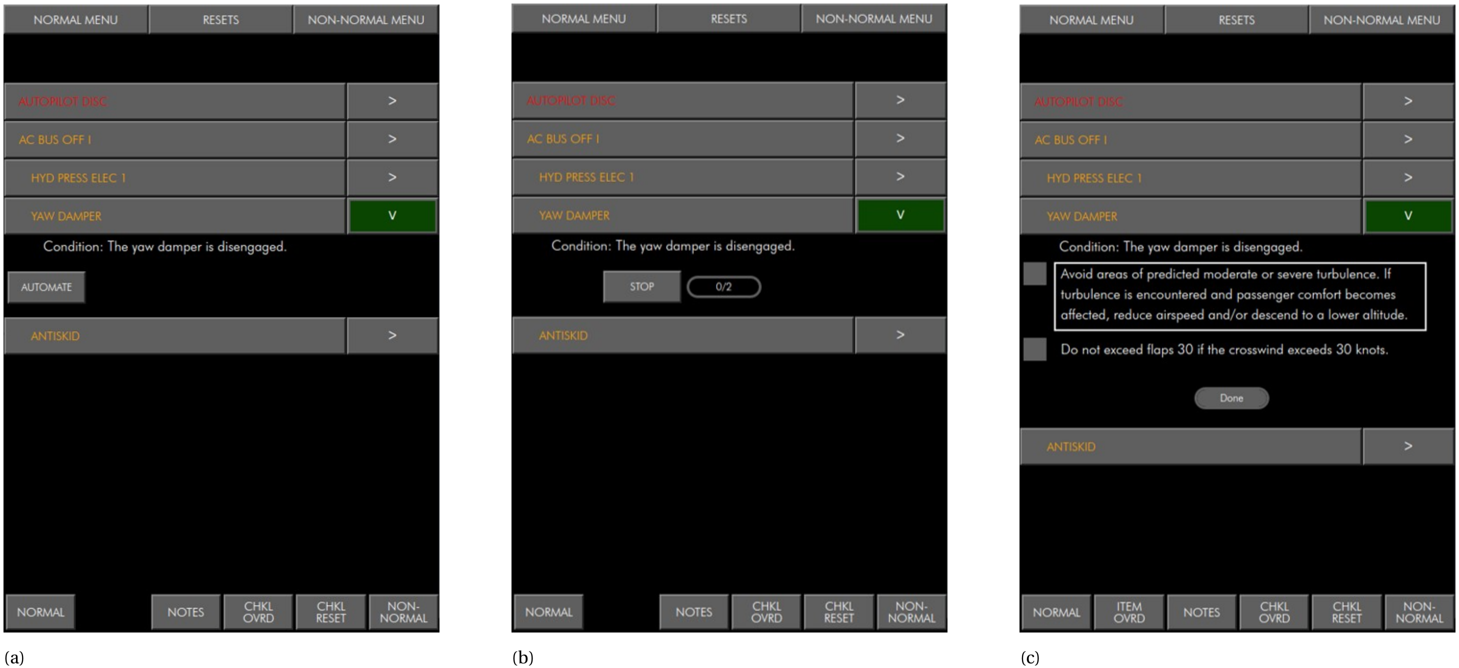
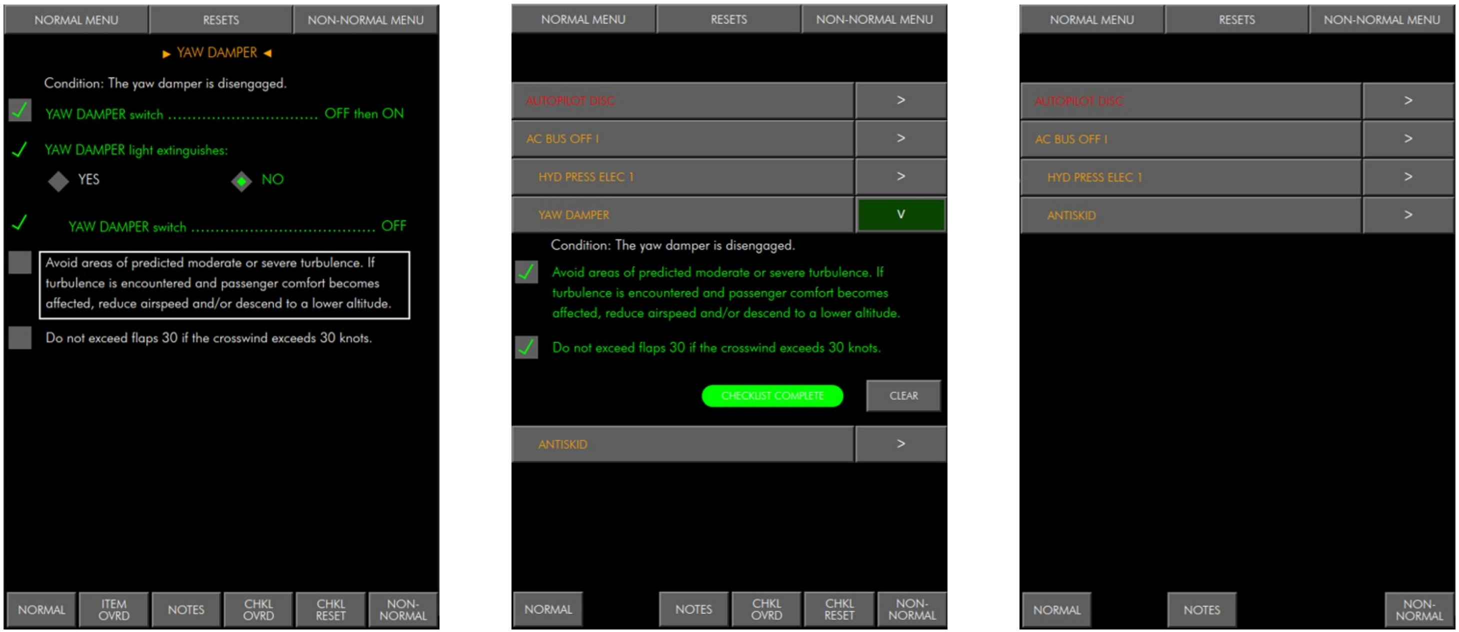


Figure 3.2: Checklist automation is started in **(a)**, in progress in **(b)**, and finished in **(c)**. Additionally, through conditional line items, the checklist content is updated in **(c)** with two more open loop line items.



(a) (b) (c)

Figure 3.3: In **(a)**, 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 **(b)**, the AECL displays a green bar stating, ‘Checklist Complete’. Finally, in **(c)**, the checklist is now ‘cleared’ from the non-normal menu

3

Due to a steep learning curve involved for learning a new display and annunciation process and to avoid scenario recognizability, 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. Furthermore, two participants were type-rated on the Boeing 787 and therefore already had experience with EICAS and the ECL. They were divided over the two groups.

Table 3.2: Information provided during experiment

Call sign	DUT 961	
Cruise altitude	FL350	
Passengers on board	87	[-]
APU	Inoperative	
Load in compartments	1,704	[kg]
Passenger/cabin bag	9,124	[kg]
Total traffic load	10,828	[kg]
Dry operating weight	41,077	[kg]
Zero fuel weight	51,905	[kg]
Take off fuel	11,133	[kg]
Take off weight actual	63,038	[kg]
Trip fuel	7,105	[kg]
Landing weight actual	55,932	[kg]

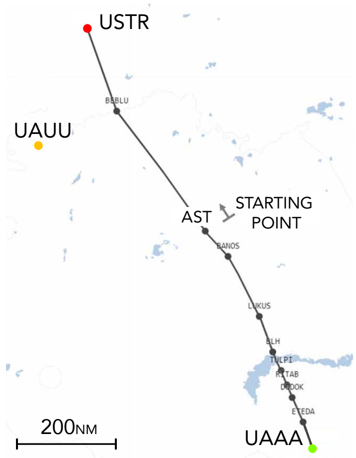


Figure 3.4: Map of the experiment flight plan

3.3.2. Tasks 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 3.4). The locations were selected to avoid participants having previous experience with the aforementioned airports. Although Global Positioning System (GPS) locations and certain airport-specific information were adopted, information about the weather, runways, and approach NAVigational AIDs (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 ILS approaches, three at USTR and one at UAUU, whereas UAUU also offered an Area navigation (RNAV) approach. However, NOTAMs communicated that the single 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 summarize, the following approaches were available per airport, at planned destination (USTR), three ILS approaches and at the destination alternate (UAUU) only a single RNAV approach. Additionally, participants were provided with key aircraft information such as weights, a call sign, and that they were dispatched with an inoperative Auxiliary Power Unit (APU) (see Table 3.2 and Figure 3.4 for an overview of the flight plan, key 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 or 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 getting 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.

In addition, the participants performed a secondary task. Six sets of prerecorded Air Traffic Control (ATC) messages were played over intervals of approximately 180 seconds during the scenario. Each of the sets included multiple messages; five sets included four messages, where only one was appointed to the participant and the others were for other traffic, and one set was appointed exclusively to other traffic. The messages requested to report a particular aircraft state or element of the flight plan (e.g., flight speed, altitude, next waypoint). The participants had to respond to the correct call sign (DUT 961, pronounced Delta Uniform Tango Niner Six One). The order and content of the messages were randomized to avoid learning effects. The secondary task increases workload, tests the ability to coordinate more than just one task, and indicates to what extent a participant is tunneled into the display.

Finally, participants assumed the Pilot Non-Flying (PNF) role and could ignore any substantial tasks generally assigned to the Pilot Flying (PF) and were thus not concerned with flying the aircraft.

3.3.3. Independent Variables

The experiment was conducted over two dimensions of independent variables, (1) checklist support, and (2) scenarios.

Checklist Support

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 multiple scenarios is important since often-trained scenarios are found to be handled much better (Burian et al., 2005). The scenarios have been verified through a high-fidelity Boeing 737-800 training device by failing the Boeing 737-800 systems as described hereinafter.

Scenarios

Generator Drive Shaft Failure In this scenario, a failing Integrated Drive Generator (IDG) on the left-hand side was simulated. This failure caused the DRIVE 1 light on the overhead panel to illuminate and the EICAS to display the corresponding message. Each IDG supplies its own bus system in normal operation and can also supply essential and non-essential loads of the opposite side bus system when one IDG is inoperative Boeing (2005). Besides the two engine generators the Boeing 737 is equipped with a third generator powered by the APU capable of supplying both Alternating current (AC) transfer busses. However, in this experiment the APU was unavailable.

Normally, if an AC source is disconnected the Bus Tie Breakers (BTBs) automatically switch to the remaining available source. However, the BTBs for this scenario were not functioning as expected, so AC transfer bus 1 did not receive the required electrical power, causing AC transfer bus 1 to be left unpowered. 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 annunciator panel. 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 window OVERHEAT lights for L FWD and R SIDE. Each of these failures has an 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.

Hydraulic Leak Failure The Boeing 737 has three hydraulic systems: system A, system B, and the standby system. They can separately power all flight controls with no decrease in aircraft controllability Boeing (2005). All three systems have a reservoir, pumps, and filters. The operating pressure is 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.

In this experiment a relatively large hydraulic leak in reservoir A was simulated, causing a loss of 10 gallons per minute. 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 panel, 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 autopilot disconnect horn sounded, however, Autopilot B was available and could be engaged. Hence, the annunciator panel illuminated both warning and caution. The electric hydraulic pump OVERHEAT light illuminated with the associated message shown on EICAS in case the hydraulic system was not shut down within approximately one minute.

A result of the unpowered landing gear is that the gear needs to be lowered by gravity, or also known as a manual gear extension (with handles under the flight-deck floor). After such operation, the gear cannot be retracted, which has a considerable impact on the fuel consumption.

3.3.4. Control Variables

In this experiment, the following five control variables were used. Both groups had to do the same **concurrent task**, which is a parallel task that 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 (Burian et al., 2005). Then, the **checklists task** is the task which is presented as per the Boeing 737-8 QRH (Boeing, 2007). These were during both scenarios similar. Both groups were comparable (within practical bounds) in **pilot** composition. They all had comparable aircraft-type rating, experience in flight hours, role, and current employer. Both groups were presented with the similar **flight plan**. This information was presented before starting the scenarios and how was communicated to the pilots similarly. Finally, **automation speed** was the same for both groups. 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 systems ample time to recognize the new configuration before advancing.

3

3.3.5. Dependent Measures

The dependent measures of the experiment were as follows.

- **Experienced workload** was subjectively measured post-scenario using the Rating Scale Mental Effort (RSME) (Zijlstra, 1993), 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) (Taylor, 1990), a post-trial subjective technique which utilizes 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 represented with the checklist completion time. Two variants of completion times were assessed. Firstly, the time to complete the entire NNC was measured, which includes the time spent on searching for information (like weather), communication, and other concurrent tasks. This variable will be further referred to as the gross time of completion. Second, the time spent on completing the checklists itself was measured. This time excluded all time spent on other tasks. This variable will be further referred to as the net time to completion. 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.

- **Choice of airport** (destination, destination alternate, or departure) was registered, as well as the time by which such decision was made.

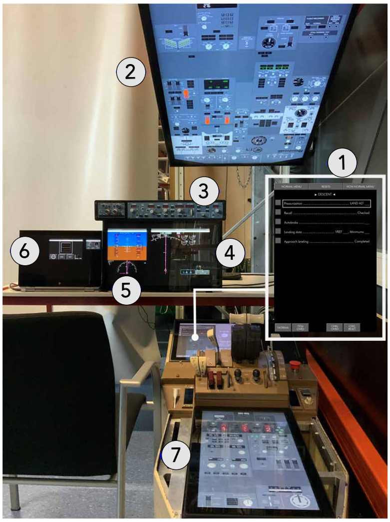


Figure 3.5: Experiment apparatus, the ECL **(1)** was positioned between the aft pedestal **(7)** and the row of displays in front of the participant. The row contained, from left to right, the master caution **(6)**, the Primary Flight Display (PFD) **(5)**, Navigation Display (ND), and EICAS, together presented as **(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.

- **Concurrent task score** was obtained by determining the accuracy with which a participant responded to the correct call sign with the correct answer.

- **Acceptance** of both displays was assessed to identify if the design was deemed effective and suitable. Following a Crew Acceptance Rating Scale (CARS) (Lee et al., 2001) flow diagram, the participant indicated a score from 1 to 10.

3.3.6. 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 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.

The displays were presented on, following Figure 3.5, **(1)** 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. The location of the information was presented as according to Figure 3.5.

3.3.7. Training

A dedicated training scenario with made-up checklists was performed multiple times to ensure the participant was fluent in navigating the display and the touch flight deck before beginning the measurement stage. To focus the training on interaction with the new display only, 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 3.1, 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 the opportunity to develop context where needed.

3.3.8. 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.

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.

3.3.9. Hypotheses

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

1. **Experienced workload** decreases as a result of automation.

2. **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.

3. **Situation awareness** remains unchanged since the checklist steps were chosen such to minimize this effect. The automated design might suffer from out-of-the-loop complications (Endsley et al., 2003) in terms of perception (pilot is not observing the switches as much) 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. It can be argued that situation awareness might even increase because of the freed cognitive resources due to the automation, which would allow for better comprehension (in the same time span), and projection of future status. Again, such effects are expected marginal since the experiment is not constrained in time.

4. **The concurrent task score is higher**, due both a lower expected experienced workload – and thus an enhanced capability to manage other tasks – and less attentional tunneling when not manually completing steps.

3.4. 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 utilized where applicable.

3.4.1. Time to Completion

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

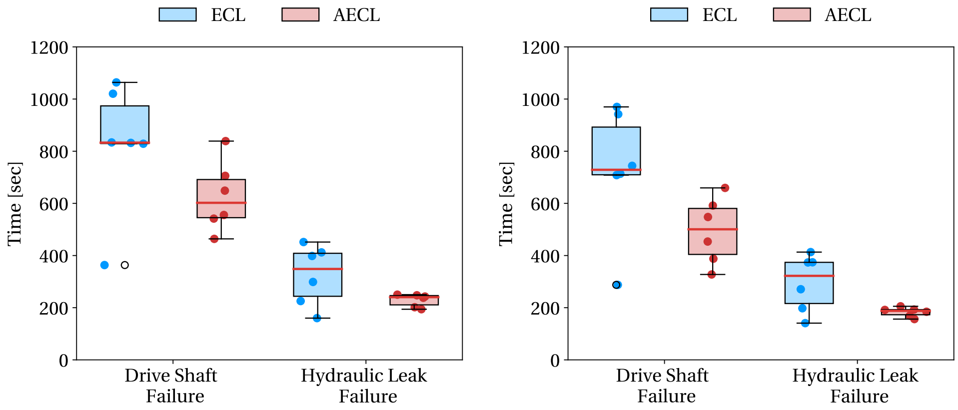
Gross Time to Completion

The gross time to completion results are visualized in Figure 3.6a. 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 ($U = 9.0$, $p = 0.087$) nor 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 (except one) of the participants using the AECL achieved lower times to completion for the drive shaft failure.

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 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.

Net Time to Completion

The net time of completion 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 data points of the AECL display decrease more relative to the ECL display, as can be observed when



(a) Gross time to completion

(b) Net time to completion

Figure 3.6: Time to completion results

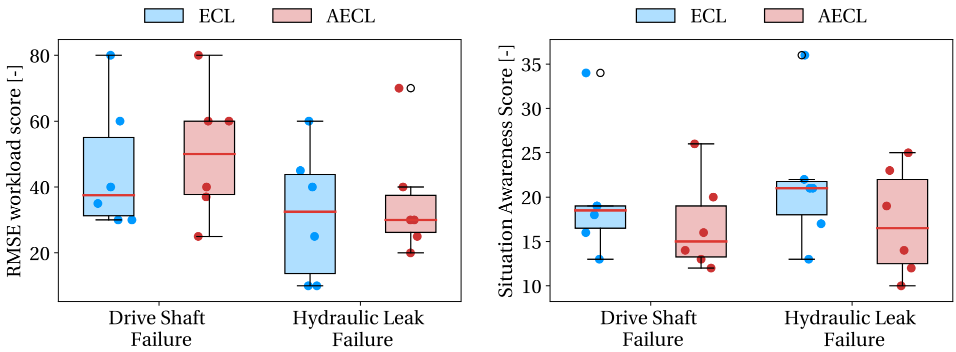
comparing Figure 3.6b with Figure 3.6a. The net time to completion medians are reduced by 31.3% for the drive shaft failure scenario (ECL: Mdn = 728.8, AECL: Mdn = 500.7) and 42.0% for the hydraulic leak scenario (ECL: Mdn = 322.1, AECL: Mdn = 187.0).

3.4.2. Experienced Workload

The subjectively indicated RSME workload per design for both scenarios is shown in Figure 3.7a, 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 3.7a 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, 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.

3.4.3. Situation Awareness

The situation awareness SART measurements are shown in Figure 3.7b. 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



(a) Experienced workload ratings (b) Situation awareness scores

Figure 3.7: Results for Workload and Situation Awareness.

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 minimize any information shown and that participants would have sufficient context 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 being out-of-the-loop and how much it positively influenced participants through freed cognitive resources to be allocated to develop situation awareness.

3.4.4. Choice of Airport

Upon experiencing a failure, participants had the choice to either continue as planned, or choose to divert to destination alternate. The departure airport was however too far to be a suitable option. For the drive shaft scenario, the checklists communicated to the pilot to *"land at the nearest suitable airport."* The 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 allowed to conduct a 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 (Etherington et al., 2016). 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. This is likely the result of the ongoing development of airline companies' risk position towards RNAV approaches. As such, both options are possible. The added distance to the planned destination is not substantially greater than diverting to the destination alternate 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 there is still hydraulic redundancy left with hydraulic system B and the standby hydraulic system after losing hydraulic system A. Moreover, both hydraulic system A and B are capable of single-handedly powering flight controls without losing controllability (Boeing, 2005). 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 riskier option.

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 3.8. The time required to form a decision is shown in Figure 3.10, 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 ($U = 7.0$, $p = 0.046$).

With the hydraulic leak failure, for both designs, participants diverted two out of six times, as shown in Figure 3.9.

Interestingly, after investigation of experiment video recordings and post-scenario commentary, none of the participants considered whether an RNAV approach was still authorized, 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. The responses were rated on completeness and correctness. All of them understood the hydraulic failure, but the generator drive shaft failure was frequently not fully understood. There was no difference found between both groups.

Factors that drove the decision included the possibility for an RNAV approach, runways availability, nearest airport, single autopilot, icing and turbulence conditions, fuel consumption increases, and no EGPWS. Again, no differences were found between the groups.

Regarding the time it took to choose an airport, Figure 3.10 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.

3.4.5. Acceptance

The acceptance scores obtained through the CARS measurement are summarized in Figure 3.11 for the ECL and AECL display. When observing the figure, the AECL has

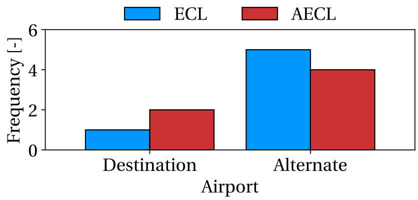


Figure 3.8: Chosen airport during the drive shaft failure scenario

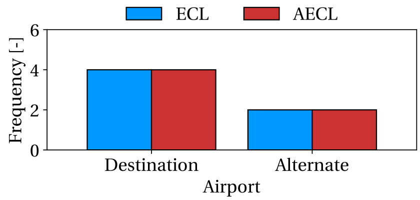


Figure 3.9: Chosen airport during the hydraulic leak failure scenario

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.

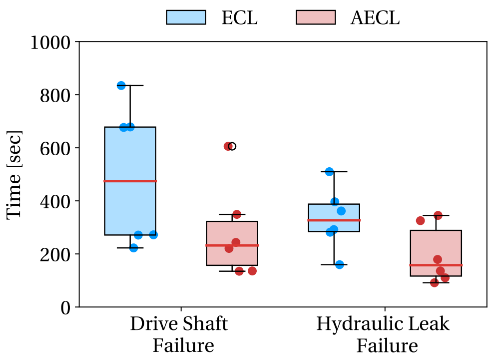


Figure 3.10: Decision time

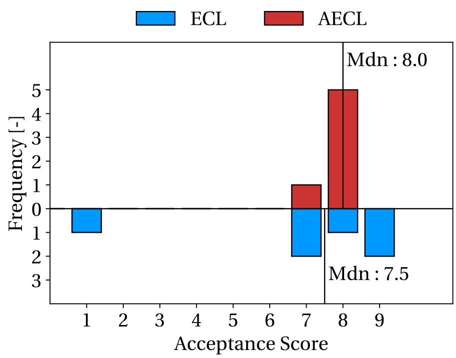


Figure 3.11: Acceptance scores

3.4.6. Concurrent Task

The concurrent task score indicates the accuracy by which a participant completed the challenge-response task. Per scenario, Table 3.3 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 3.3 shows little difference between both designs for the concurrent task accuracy.

Table 3.3: Correct or incorrect completion of the concurrent tasks per participant after introduction of a failure

	Participant	Drive shaft failure 1	2	3	4	Accuracy[2]	Hydraulic leak failure 1	2	Accuracy[3]
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%	

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 ($U = 14.0$, $p = 0.261$).

3.5. Discussion

The goal of this research was to investigate the effects increased levels of automation for the ECL during non-normal situations, an attempt to achieve lower workload and time requirements, while maintaining situation awareness. Results revealed that particularly checklist completion times and the final decision-making times were significantly reduced.

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 time saving 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 31.3% 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 completing the checklist. On the other hand, the gross value does

[2] Only includes the first three data points
[3] Only includes the first data point

include factors such as the participant rationalizing 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 (Burian et al., 2005).

Etherington et al. (2020), 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 realized approximately 30% time reductions, despite the distinctively different approach taken. However, Etherington et al. (2020) 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 (2011) 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.

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 authorized 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 (Kramer et al., 2018), after careful joint review by several participants, not all airlines prescribe the RNAV approach as unauthorized in such case.

Notwithstanding, in all cases the operational consideration —whether RNAV approaches were still approved— was non-existent. Plausibly, this is because 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. (2018). 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, 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 (Burian et al., 2005) and deal with higher troubleshooting times found for SPO conditions (Etherington et al., 2016). Moreover, comparable experienced workload and situation awareness was observed, but the measurements were realized 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.

3.6. Conclusions

To better support pilots during non-normal event resolution tasks, this research proposes system management support with elevated levels of automation (AECL) compared to the current state-of-the-art (ECL) which was tested through a human-in-the-loop experiment against a reproduced Boeing 787 ECL & displays with 12 commercial pilots when assuming the Boeing 737 systems and flight deck hardware. Significant reductions in checklist completion and decision time 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 with an AECL 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 (yet) found, supported by comparable decision-making outcomes between both designs. Although initial results are promising, participants unanimously indicated a need for more feedback from the automation. It is proposed for next design iterations to better communicate automation outcomes. However, based on this cautious attempt, we conclude that automating system management tasks workload can significantly be reduced and not harm situation awareness. More radical designs with higher levels of automation have the potential to further reduce workload, and paving a way for workload-limited operations, such as RCO.

References

Bainbridge, L. (1983). Ironies of automation. *Automatica*, 19(6), 775–779.

Boeing (2005). *737-600/-700/-800 Flight Crew Operations Manual.* Seattle, Washington, USA: The Boeing Company.

Boeing (2007). *Boeing 737-800 Quick Reference Handbook.*

Burian, B. K. & Barshi, I. (2003). Emergency and Abnormal Situations: A Review of ASRS Reports. In *Proceedings of the 12th International Symposium on Aviation Psychology* Dayton, Ohio: Wright State University Press.

Burian, B. K., Barshi, I., & Dismukes, R. K. (2005). The Challenge of Aviation Emergency and Abnormal Situations. *NASA Technical Memorandum*, (June), 1–21.

Endsley, M. R., Bolte, B., & Jones, D. G. (2003). *Designing for Situation Awareness: An Approach to User-Centered Design.* CRC Press.

Endsley, M. R. & Kaber, D. B. (1999). Level of automation effects on performance, situation awareness and workload in a dynamic control task. *Ergonomics*, 42(3), 462–492.

Etherington, T. J., Kramer, L. J., Bailey, R. E., Kennedy, K. D., & Stephens, C. L. (2016). Quantifying pilot contribution to flight safety for normal and non-normal airline operations. In *AIAA/IEEE Digital Avionics Systems Conference - Proceedings.*

Etherington, T. J., Kramer, L. J., Young, S. D., Evans, E. T., Daniels, T. S., Barnes, J. R., & Santiago-Espada, Y. (2020). Information Management to Mitigate Loss of Control Airline Accidents. In *AIAA Scitech 2020 Forum*, number January (pp. 1–19). Orlando, FL.

Kramer, L. J., Etherington, T. J., Bailey, R. E., & Kennedy, K. D. (2018). Quantifying Pilot Contribution to Flight Safety during Drive Shaft Failure. In *Advances in Intelligent Systems and Computing.*

Lee, K. K., Kerns, K., & Bone, R. (2001). Development and Validation of the Controller Acceptance Rating Scale (CARS): Results of Empirical Research. In *4th USA/Europe Air Traffic Management R&D Seminar* (pp. 1–9).

Li, W. C., Cao, J., Lin, J. H., Braithwaite, G., & Greaves, M. (2017). The Evaluation of Pilot's First Fixation and Response Time to Different Design of Alerting Messages. In *International Conference on Engineering Psychology and Cognitive Ergonomics* (pp. 21–31).: Springer, Cham.

Parasuraman, R., Sheridan, T. B., & Wickens, C. D. (2000). A Model for Types and Levels of Human Interaction with Automation. *IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans*, 30(3), 286–297.

Taylor, R. M. (1990). Situation Awareness Rating Technique (SART): The Development of a Tool for Aircrew Systems Design. In *Situational Awareness in Aerospace Operations* chapter 3. France: Neuilly sur-Seine: NATO-AGARD.

Thomas, L. C. (2011). Pilot Workload under Non-normal Event Resolution: Assessment of Levels of Automation and a Voice Interface. In *Proceedings of the Human Factors and Ergonomics Society 55th Annual Meeting* (pp. 11–15). Las Vegas, Nevada.

Zijlstra, F. R. H. (1993). *Efficiency in Work Behaviour: A Design Approach for Modern Tools.* PhD thesis, Delft University of Technology.

4

Applied Cognitive Work Analysis for Commercial Flight Operations

What information is needed to effectively support operational decision making?

In the previous chapters, the tasks of the pilot and the currently used flight-deck supports were studied. It was pointed out that cognitive support systems can be enhanced to (1) reduce workload resulting from system management tasks and (2) improve flight plan management support.

The design of this automation and cognitive support can be guided by a framework called Applied Cognitive Work Analysis (ACWA). *The first step in this framework is the creation of a model, which maps goals and functions within a work domain. From this model, cognitive, information, and representation requirements for a display interface can be derived. The principle behind* ACWA *is to provide the operator with an improved understanding of the work domain, which inherently improves the decision-making performance of the operator.*

This chapter will provide the results of the ACWA *performed for commercial flight operations and follows a stepwise structure similar to that of the design framework. However, the last step —to translate the requirements to the visual form— is presented in Chapter 5.*

4.1. Introduction

Today's average smartphone has five-hundred times more memory available compared to the Boeing 737 classic's Flight Management System (FMS), which has a memory capacity of just under two-hundred kilo bytes and limited computing power. The development of newer and more powerful computing hardware solves the previously existing limitations of storing and processing information. This computing power, together with large touch displays (as introduced on the Airbus A350), and new communications systems, enable many new possibilities to present and interact with information on the flight deck. Despite all these benefits, these technological advances can introduce potential pitfalls. An abundance of information can easily lead to cluttered interfaces, which can overload the pilot, and thus endanger the overall effectiveness of the human-machine system. Simply adding new features and information is, therefore, not the way forward. Instead, before making any adjustments, designers should rethink how the information presentation on the flight deck should be adapted to fit the capabilities (both physically and mentally) of the pilot, such that s/he can perform his or her job effectively. The technology should be adjusted to fit the users, not the other way around —the main principle of human-centered-design (Billings, 1996).

Currently, the main role of the pilot is one of a decision-maker and a flight-plan manager. He or she is the ultimate responsible person for the wellbeing of the passengers and efficient outcome of the flight. However, a lot of information needs to be combined and processed to make informed decisions about the remainder of a flight. This is not an easy job (Reitsma et al., 2017), especially under dynamic, time critical, or non-normal conditions. Relevant information that is described in a myriad of documentation and presented in various forms, and on various displays on the flight deck needs to be integrated by the pilot to make fully informed decisions.

Recently introduced systems, such as ROPS and EGPWS, aimed to ease the decision-making process. These recently introduced systems are tactical, task specific, and focus on one aspect of the flight-plan management task (e.g., supporting ground operations, landing calculations, or avoiding terrain collisions). However, support for the flight-plan management task as a whole —the strategic part of the pilot's job— is due to this stepwise approach out of scope.

The following issues can be observed if the flight deck is reviewed holistically on how it supports operational decision-making. First, different systems on the flight deck alert all in a different place and format. For example, the are notes on the ECL, alerts on the PFD, terrain warnings on the ND, fuel and instrumentation warnings on FMS. Where EICAS was introduced to present messages in a centralized location, flight-plan management alerts are spread out over the systems and displays. Second, not all consequences or impacts on the flight plan are alerted by the supports leaving gaps to be filled by the pilot, which creates the risk for unconsidered impacts. Next, alerting is currently much focused on the system level, for instance describing quantities of hydraulic fluid, instead of a functional level (i.e., what can and cannot be done anymore).

Therefore, if the main role of the pilot is to manage the flight plan and make adequate decisions; why not support this task better and make it the primary focus of the flight deck displays?

Hence, this study aims to determine what information needs to be presented by flight-plan-management supports to aid the pilot in its role as a decision-maker for commercial flight operations. This study will take a holistic approach; the cognitive work performed in flight operation will be studied. From this analysis, a subset of requirements will be created that can be used for a future display design of a decision support tool —an operational decision-making support. Identifying what information needs to be presented can be done in many ways. The objective is to design a decision support system that intuitively aligns with the human user's perceptual and cognitive processes.

4.2. The Ecological Approach

Research in interface design can be categorized into three parts: user-driven, technology driven, or problem driven (Bennett, K.B. and Flach, 2011). User-driven approaches aim to improve the usability and esthetics of a display (i.e., the look and feel) and the interaction with the world – the task – is often simple and deterministic (Norman, 2013). However, when the problem becomes complex, it becomes unpractical or even impossible to specify a task for each unique condition (Burian et al., 2005). Hence, another approach is required to design interfaces for complex problem solving, namely, a problem-driven approach. In such approach, the interface design is based on a thorough understanding of the constraints in a work domain and the (cognitive) work that needs to be performed within this domain (Elm & Potter, 2003). Presenting the operators with these constraints allows them to redefine their own tasks based on features of the work environment (Rasmussen et al., 1994).

In this chapter, the focus of analysis is on the interactions between system and environment rather than the interaction between machine and human. The analysis in this chapter will not include the last step of the analysis, which is translating the objective set of requirements into a visual form. This is because design for form or usability is a process that requires skill and artistic creativity. The designed end product will be different for every designer; it is highly susceptible to change whereas the analysis and the derived requirements are more of a fixed, objective nature.

4.2.1. System-Environment Interactions

Controlling something in the world (doing work) can be achieved with predefined procedures. Procedures work well in conditions that are exactly as the predefined conditions, such as predictable, stable, and simple applications. These applications are good candidates for a task-based approach. In such applications, the procedure will lead to successful control. However, for dynamic and complex applications, defining procedures for each possible case is practically impossible, because of the endless possible conditions. The outcome cannot be guaranteed since the actual conditions can differ from the predefined conditions —making a predefined task worthless.

In the case of flight-plan management, the environmental conditions, the flight plan, state of the plane's systems are always different due to the chaotic nature of the world. Take for example an instruction like: 'If a thunder cloud is in front of you, turn right.' This might avoid the adverse weather, but what if there is a mountain on your right? So, if these instructions will be followed blindly, the outcome might be unsuccessful, to say at least. Hence, a task-based approach does not provide a robust solution for flight-plan management applications.

An example of a task-based approach in flight-plan management is as follows. Airlines use in their operations escape routes to provide guidance in case certain abnormal conditions exist. For example, an engine malfunction above high terrain. These escape routes can be followed to avoid collisions. However, these task-based approaches only work if no other hazards are present on that route (e.g., bad weather or traffic). They provide aid; work most of the time but cannot guarantee a successful outcome.

Instead, the effects of the system and its environment should be observable to allow the user to solve problems by themselves, whatever they encounter; and they will determine their own tasks or adapt procedures.

Showing an accurate mapping of the interactions between the system and the environment will allow the user to determine when his or her goal is being successfully achieved, and when not. The user can in this case adjust the system inputs or plan accordingly. The display should capture each element in the world that affect the user's plan and should present how the elements can be manipulated to achieve goals.

Humans solve complex problems with the use of a mental model. People process information top-down and bottom-up (Rasmussen, 1983). In the top-down process people start with goals and pay attention to environmental elements that could achieve their goals. Whereas with bottom-up reasoning, the process starts with an observation from the environment to predict the effects on their goal.

Within the field of ecological psychology, the believe is that people actively look for *affordances* [1] of the elements around them to achieve a certain goal. An affordance is a *relation* between the properties of an object and the capabilities of the agent which determines how the object could possibly be used to reach the goal (Norman, 2013). Affordances should be perceivable to support effective problem solving. Ideally, affordances are derived from clues in the world that people simply pick up through *direct perception*. Perceived affordances help people to figure out what actions are possible without the need for labels or instructions; they become intuitive.

4.2.2. Ecological Interface Design

Providing an overview of the *affordances* in a work domain is the main principle behind the Ecological Interface Design (EID) method (Vicente & Rasmussen, 1992). It is compatible with how people solve problems in the real world.

The framework is structured around two questions. The first being, what is a psychologically relevant way of describing the complexity of the work domain? And second, what is an effective way of communicating this information to the operator? The formalism to describe the work domain used by EID is the Abstraction Hierarchy (AH). The Skill, Rule, Knowledge (SRK) taxonomy is used as a guideline for the visual representation.

The AH is used to mimic the mental model or 'knowledge model' that the user should have to effectively perform a task. It organizes the work domain into five levels, on the

[1] First introduced by J.J. Gibson and describes it in his 1979 book: "The Ecological Approach to Visual Perception"

top, functional purposes, and the bottom, physical form of elements. This is done to stimulate both top-down and bottom-up reasoning.

The AH captures the relevant affordances and its elements in the work domain to achieve the intended goals. Abstraction is used to understand the complexity of the work, it removes the levels of detail to capture the most essential features of a system. The interactions between the various functions and elements are captured by asking; "Why?" (For the level on top), "What?" (For the level under consideration), and "How?" (For level below). This will provide means-end links that give the user guidance to reason through the system (top-down and bottom-up).

Although the AH is a powerful reasoning tool, it was found to have some limitations to map the entire flight operations commercial domain (Reitsma et al., 2019). It was found difficult to map all links in one AH. Furthermore, the five layers seem to be too restrictive. Links can result into circular means-end links, which are not allowed in hierarchies. And lastly, the clarity of the final artifact does not seem to be as useful as intended due to the entangled lines and links.

The SRK taxonomy is prescribed as the guideline to present information on various levels, but not many use this in their design process —they see it more as a recommendation— nor strict guidelines exist to determine what information should be on the display and what not. The link between the AH and the visual form or display is therefore sometimes not clear, and relies much on the practitioner (McIlroy & Stanton, 2015).

Instead for this study a stricter, stepwise process was chosen to guide the design process. The method of choice for this study is the Applied Cognitive Work Analysis (ACWA), which will be elaborated upon in the next section.

4.3. Applied Cognitive Work Analysis

The Applied Cognitive Work Analysis (ACWA) was developed by Elm & Potter (2003). It is based on other modeling and design methods developed by Lind, Woods, Hollnagel, Rasmussen, and Vicente. The ACWA combines Cognitive Task Analysis (CTA) with Work Domain Analysis (WDA) techniques, to a streamlined design process for decision support systems. It was intended as an pragmatic and effective design process, but has been applied in only a few studies so far (De Filippis et al., 2014; Mondragon Solis & O'Brien, 2011; Potter et al., 2003).

Foundations

A decision support system should present the information needed by the decision maker, can be controlled effortlessly, complements the cognitive power of the human mind, and support problem solving (Elm & Potter, 2003). The ACWA has four underlying premises (Elm & Potter, 2003, p. 4–5) that distinguish it from other methods:

> Premise 1: Humans form a mental model of the domain as part of their understanding and problem solving.
> …
> Premise 2: The decision support system must itself embody a "knowledge model" of the domain that closely parallels mental models representative

> of expert human decision-making.
> ...
> Premise 3: An effective decision support system knowledge model is composed of functional nodes and relationships intrinsic to the work domain.
> ...
> Premise 4: An adaptation of Rasmussen's abstraction hierarchy provides the needed representation of the abstract functional concepts and relationships to form the basis for the decision support system functional knowledge model.

The knowledge model is transferred into cognitive work requirements from which in a stepwise process representation design requirements are derived. These requirements are sequentially transferred into a visual from. Note that, the approach is still an iterative process.

Functional abstraction network (FAN)

As was being stated in the premises, a knowledge model of a work domain needs to be developed. This knowledge model is described in ACWA by a Functional Abstraction Network (FAN). The FAN is a goal-means decomposition, which is based on the work of Woods & Hollnagel (1987) (Elm & Potter, 2003). Vicente & Rasmussen (1992) considered the FAN as an alternative to the AH used in Ecological Interface Design (EID). Furthermore, the FAN also has similarities with Multilevel Flow Modeling (MFM) introduced by Lind (1994), but the strict use of flows, such as mass and energy, are excluded. Instead, each function controls its own commodity, which can still be mass and energy, but also money, health, or space.

A functional node is a combined goal-process pair, and each process consists of various functional operations that manipulate the commodity at stake. Sources, Sinks, Storages, Transports are used in this study, but many more exist. Each functional node (goal-process pair) can influence other nodes, even a specific part of the process can be linked to another node. By creating such a mapping, the effects are precise and localized. The functional nodes become a network of functions and goals, on several layers of abstraction, where the top is normally a high level of abstraction and the bottom a lower level. The goals can be obtained with an objective tree, which can be obtained by asking question as, *how?* for the lower nodes, and *why?* for the upper nodes. This modeling can continue until the practical boundaries of the domain are reached. These objectives can be understood by interviewing and observing subject matter experts, reading operation manuals, and studying system documentation.

Each functional node can have their own commodity of what the process is controlling. These functional nodes and the used functional elements are shown in Figure 4.1. A commodity can be introduced from the world to the controlled system through a source block. The transport inflow block can manipulate the commodity (e.g,. a pump). Furthermore, the commodity can be stored in a storage. Another functional block is the transport outflow block, for example another pump, which can transport a part of the commodity to a sink to be disposed and placing it outside of the boundaries of the controlled functional node. This simple cycle can be done for many commodities, for example money, health, spaces, and paths. Take for example money; there is a large

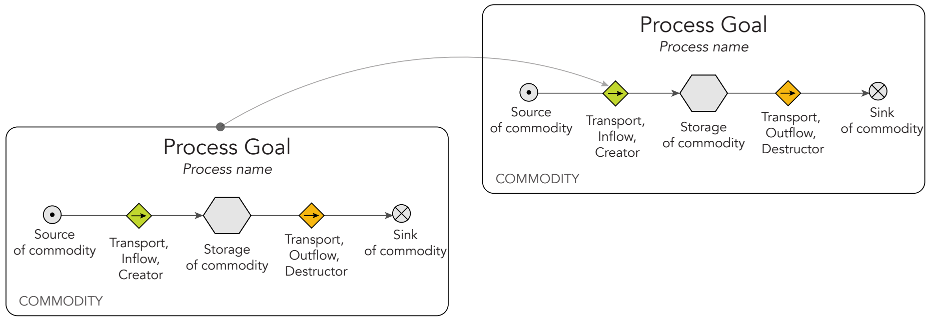


Figure 4.1: Template of the functional nodes, their connections, and the process with the various functional operators.

amount of money in the world, however, this becomes only available if it transferred to your bank account (e.g., by sales, gifts, investments). By spending something you transfer the money outside of your reach (i.e., a sink). After the transfer this money cannot be used by you anymore, however, it can act as a source for another block and thus creating a network of functional relations.

Cognitive Work Requirements (CWR)

After the development of the FAN, cognitive demands for each part of that domain model can be determined. They refer to tasks an operator needs to perform during the decision-making, problem solving process. These include monitoring, controlling, selecting, observing, analyzing for abnormalities, planning, thus basically all actions that a user needs to perform. Each node, goal and component can have Cognitive Work Requirement (CWR).

Information / Relationship Requirements (IRR)

"Information / Relationship Resources (IRRs) are defined as the set of information elements necessary for successful resolution of the associated CWR" (Elm & Potter, 2003, p. 22). It does not list sensors or instrumentation, but determining what information is required to perform the cognitive work. A IRR is focused on satisfying the cognitive demands specified in the CWR. Important to note is that IRRs are not limited to the data currently available in the system, instead identifying IRRs can drive installation of sensors or development of models.

Representation Design Requirements (RDR)

The penultimate step in the ACWA process begins the shift in focus from 'what' is to be displayed to 'how'. The Representation Design Requirement (RDR) scopes the IRRs to the intended supported tasks (a region in the FAN). A RDR states what should be presented, with annotations of importance and priority. This is important for display real estate allocation, and attention allocation of the displays. The RDRs also includes descriptions of how the information is presented (i.e., with mode is used; audio, visual, or haptic). It further includes all IRRs, but with added detail on how to present these. This will be the main artifact that will be used by other engineers/developers.

Presentation Design Concepts (PDC)

The last part is the more artistic phase that also requires knowledge of usability and perception. The decision support will obtain its form and physical appearance in this step.

4.4. Functional Abstraction Network

The process and theory of ACWA was described in the previous sections. In the upcoming sections, this will be applied to map goals and functions of the work domain *commercial flight operations*. The process starts with the development of the knowledge model and the process of building the knowledge model initiates with identifying the top-level goals and commodities. These goals and commodities are defined by studying the overarching entity of the work domain, which is a commercial entity.

4.4.1. Key Values

A commercial organization, like an airline, has the purpose to create or increase value. This value can be created by providing a service like transporting people or cargo. This value can only be collected (sold) if the service is what people want, for instance a flight to a specific destination. However, this service needs to be safe, realized by arriving on time, and the comfort level needs to be as promised. The value is determined by how well these factors are achieved, but it can be influenced by the reputation of the company. Here reputation can be seen as the product of collected satisfaction and marketing.

The satisfaction of passengers can be influenced by operating according to —or ahead of— the expected **schedule**, providing the promised **comfort**, lowering prices (or providing compensations), and ensuring safety throughout the whole process. A company wants to maintain the ability to produce and offer the service. Laws and regulations need to be followed to protect the ability to produce, if not a shutdown or fines will be enforced. Hence, the airline needs to **comply** with these laws. One of these laws are not to harm people (guarantee **safety**), which has top priority in aviation. People's health can be protected by not colliding or damaging the plane, and at the same time providing safe conditions (e.g., not too hot, not too cold, and providing breathable air). Moreover, damaging the plane adds costs and might endanger the continuity of the operations.

These costs are of interest for the business and not necessarily for the passengers once a ticket has been bought. The business tries to keep the **costs** low since this way more value can be stored. Managing these five key values is the main priority for an airline company.

The FAN for commercial flight operations is shown in Figure 4.2. The key values are captured with the following nodes (see Figure 4.2) safety (node 5 and 7), compliance (node 3), schedule (node 4), costs (node 1), and comfort (node 6).

4.4.2. System health

Maintaining or maximizing the health of the systems is the main priority for the system management task pilots need to perform. Each system and component have specific limitations for the operating temperature, pressure, electrical loads, quantities, vibrations, and structural loads. Any fire, blockage, leak, short circuit, excessive load needs to be avoided to prevent damage. The system health can be protected by providing cooling, heating, lubrication, pressurizing, load management, and providing fire protection. Despite all these efforts, systems are subjected to wear and tear. After a certain time, maintenance or replacement of components is inevitable, which is moreover prescribed by regulations. Furthermore, resources like fuel, stored electricity, and fluids are depleted after a certain time (depending on the usage). Therefore, the system health can only be ensured for a certain **time**.

The system health and protection of the airplanes capabilities can be ensured with redundant systems. If in any case a failure occurs, other systems can take over the functional —or part of the functionality— to ensure sufficient performance to protect the passengers from harm. This is shown in Figure 4.2 as the functional node block 7.

4.4.3. Passenger health and comfort

Humans, like systems, have specific limitations and needs. These all need to be met to prevent harm. This includes providing shelter, providing a breathable environment within comfortable temperature limits. This is all done with a pressurized cabin (including doors, locks, seals), and the air conditioning system. Any toxic fumes, smoke or gasses threaten the people on board of a plane, hence emergency oxygen is provided.

The needs of people need to be met not only to protect against harm, but also to provide a comfortable experience. Hence, lavatories, entertainment, and food services are provided onboard. But here again, these safety and comfort levels can only be ensured for a period of time since after a long period of time people get bored and cramped in their seats, which can even lead to impaired health (Gavish & Brenner, 2011).

4.4.4. Space & Path

The high levels goals can be achieved not only with system management but (obviously) also with the flight operation itself (moving from a to b). The operation entails, moving passengers from the departure gate through **space** among a **path** with a certain **velocity** to arrive on **time** at the destination.

The principle of path and space are the key abstract concepts in flight operations. The system (plane) has the affordance of motion. The system and its capabilities result into a maximum and minimum speed, turn radius, accelerating and stopping distance, climb rate, etc. This will limit the possible motion and therefore the paths that can be performed.

These paths, however, are within a space. Although space is in theory unlimited, elements in the environment will restrict this space. These elements can be physical, such as terrain, or virtual, like a control zone. The possible paths are largely restricted by these spaces. Paths crossing a certain space that is hazardous or not allowed will no longer achieve the goals, such as safety and compliance, respectively. The world is full with paths and space constraints that can jeopardize a successful outcome of the operation. This is an important concept in the functional analysis.

Paths and spaces can be constructed (made possible) or can be destructed (made impossible). For some types of paths and spaces, it is possible to make them satisfac-


COSTS
SCHEDULE
COMFORT
SAFETY
COMPLIANCE
Maximize Created Value
Business management
Capital
Investments
Captured Value
Direct Operational Costs
Lost value
Potential Service Value
Sales
Other costs
VALUE
Maximize Reputation
Managing customer saftisfaction
Potential Reputation
Satisfied Customers
Captured Reputation / Satisfaction
Unsatisfied Customers
Lost Reputation
REPUTATION
Arrive at Destination on time
Manage arrival time at destination airport
Potential Time savings
Operations Shorter than Expected
Planned Arrival time
Operation Longer than Expected
Delayed Time
ARRIVAL TIME
Deliver Expected Comfort Level
Manage comfort levels
Potential Comfort gain
Systems & Service
Operations
Comfort Level
Lost Comfort
COMFORT
Maintain Sustained Production
Complying with regulations, airworthiness
Serviceable Routes, Planes
Comply with regulations
Production Capacity
Violations
Lost Production
AVAILABLE SEATS
Protect Passenger & Crew Health
Maintaining passenger & crew health
Health at Boarding
Medical Assistance
Passenger & Crew Health
Harm
Lost health
HEALTH
Maximize System Health & Airplane Capability
Maintaining airworthiness
Health at Dispatch
Maintenance / Servicing
Redundant Systems
System Health
Recoverable System Functionality
Damage, Spent Resources
Lost health
SYSTEM HEALTH
Fire protection
1
2
3
4
5
6
7

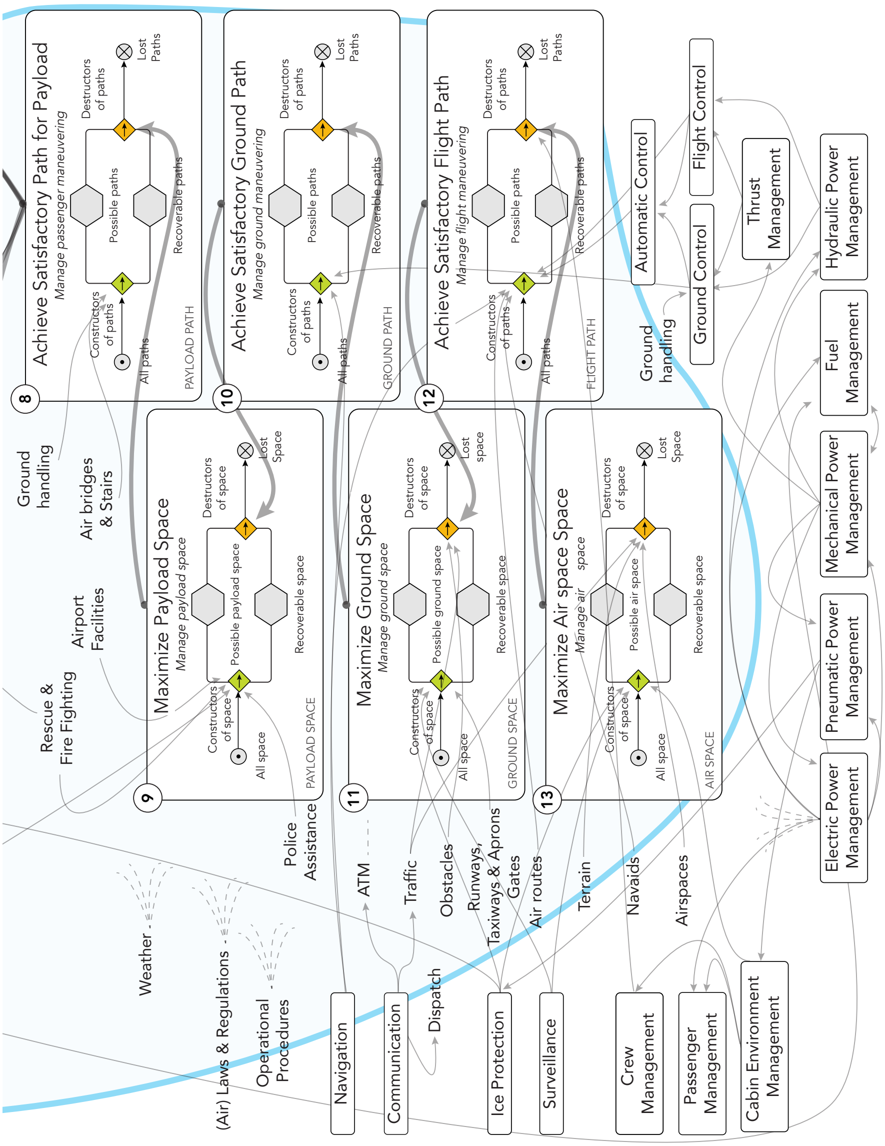


Figure 4.2: Functional Abstraction Network for commercial flight operations. The blue marking indicates the focus area of the decision support system.

tory again. For example, by requesting authorization (or clearances) a space or path can open up. Moreover, in the case of emergencies, some path restrictions such as noise abatement procedures, can be overruled to save the aircraft and the people on board. On the other hand, some spaces are permanently unavailable for flight. These are spaces occupied by terrain, obstacles, and traffic.

The movement along a path can be split up into three domains, which are inherently different from one another. These domains are the (1) passenger or payload maneuvering domain, (2) ground maneuvering domain, and (3) flight maneuvering domain. During the first and last part of the operation, the affordance movement is done by the payload (i.e., passengers or cargo). Passengers can walk but are limited by their step size. Boarding the plane, therefore, is done with stairs or air bridges. Cargo, however, requires a whole different set of equipment to move (e.g., conveyer belts, ground handling personnel).

However, payload also has its limitations and restriction in terms of space. It requires a temperature within limits, preferably protected from weather elements like wind and rain. The payload can also be restricted from a regulatory perspective. Some people with certain visas are allowed, where others are not. The same holds for cargo. In case of an unruly passenger, police assistance is needed. And, when a passenger is feeling unwell s/he requires medical assistance. Some gates can offer these facilities, and some do not (e.g., desolate airport in the desert). The ground facilities dictate for a large part if the gate (destination) is suited for the payload or not.

Once all the passengers are onboard, the plane taxis to the runway. The movement in this case is done by the plane, either with or without assistance. The movement is restricted to the horizontal plane (lateral, longitudinal). The plane has a landing gear that affords rolling and determines the turn radius. The dimensions of the plane, furthermore, determine what paths are possible without collision. The ground space is restricted by the supportive surface, the runways, taxiways, and apron. The combination of the type of tires, weight of the plane and the pavement need to be a fit (i.e., using the Aircraft Classification Number (ACN) and Pavement Classification Number (PCN) method). The plane determines the suitability of the ground space. The paths, and thus movement on the ground, is heavily restricted with markers on the taxi ways, runways, and aprons. They can be seen as predefined paths that help the crew to determine a non-colliding path. Certain areas and paths are restricted by ATC and can be opened with authorization. Another important part of the ground operation is the transition from ground operations to flight operations and vice versa. The conditions of the runway and the performance of the plane play a key factor in this. Traffic can be considered as a dynamic space moving in time, with a virtual space around the traffic to provide separation. Runways and gates can be occupied (time slots) and it is, therefore, important to take the time factor into account for ground space. The time factor is also important since airports and therefore runways, have operating hours.

A plane has the capability to fly, hence the third domain with the same principles of space and path. The combination of environmental conditions and the plane's capabilities create a satisfactory space. However, space is limited by many factors, which can be hazards environmental conditions (e.g., icing areas, turbulence, or conflict zones), or through regulations to protect separation (e.g., Minimum Sector Altitude (MSA), or

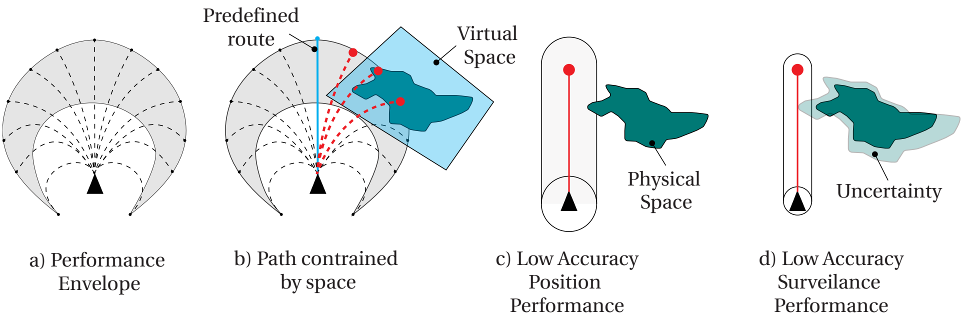


Figure 4.3: Spaces and paths.

flight levels). These limits are presented in Figure 4.3. Regulations can make spaces unsuitable for operation. However, certain spaces can be opened —made available— by requesting clearance from the governing authority. Furthermore, there are systems that increase the operating space, such as the pressurization system, anti-icing systems, or communications systems. The flight paths are limited by the accuracy of the system for determining the positions of the own-ship and the surveillance of hazards conditions such as terrain or precipitation. The affordance of flying comes from other functions like flight controls, thrust control, etc. They determine the unrestricted operating space. Unlike on the ground, airspace is more limitless. However, predefined paths have been established to ease the task of choosing a suitable path. Path is a four-dimensional construct. Path restrictions are on the longitudinal, lateral, and vertical plane. Besides these, velocity and time are constraints that influence the operation.

The entire set of path and spaces (air, ground, and payload) need to satisfy the higher-level goals. It obviously does not make sense to proceed to a gate at an airport where people cannot de-board. The air path, ground path, and payload should not be crossing any unsatisfactory spaces. Satisfactory spaces and path are defined by the higher-level key value they support (i.e., safety, schedule, cost, compliance, comfort). Conducting the flight following safe paths in a safe operating space should the top priority of the pilot. The safety value has the largest impact since it has the potential to put an airline out of business. The goals related to the other values (comfort and cost) are often jeopardized to guarantee safety.

Then, there are the compliance space and paths. Crossing non-compliant space will lead to a violation of the rules and laws. Or performing a certain path, such as an instrument approach, without the required equipment. This value should be followed to avoid losing the licenses to operate. However, with these spaces and paths there is already more flexibility and depends on how strict an individual is. Take for example a traffic light. The path to the other side of the street becomes a non-compliant path once the light turns red. Despite this many people take the risk and cross the red light. Hence, in case of great urgency the regulations could be broken.

Next, a flight without arriving to the targeted destination is not a very successful flight from a commercial and customer perspective (although pilots might disagree since the first thing a pilot learns in pilot school is “a good landing is a landing where you can walk away from"). This restricts the (ground) space and paths significantly. However, it is not uncommon in case of emergencies that these constraints are dropped for the sake of safety, and the aircraft diverts to an alternate field.

Next in-line, in terms of priority, are the paths and space that will ensure comfort and lower the costs for the organization. Pilots must make a trade-off between multiple constraints. For example, a faster flight might let more passengers meet their connecting onward flights, at the expense of fuel costs. This constant trade-off is what makes it difficult for the automation, even-though operating procedures exist to guide the pilot this process requires years of training.

4.4.5. System Capabilities

The affordance of movement and available space is provided by the system capabilities. Inoperative functions can lead to a reduced performance envelope and therefore reduced operating space, or paths. The pilot has to alter his or her plan when such conflicts occur.

Pilots need to know if a certain capability is available and can be used. Critical components in aircraft are often equipped with double or triple redundancy. It is important to understand when a function is lost or close to being lost.

4.5. Cognitive Work Analysis & Information Requirements

The functional modeling efforts from the FAN are translated into CWRs and IRRs, as shown in Tables 4.1 – 4.8.

For simplicity, the focus is put on the safety and compliance aspect of the operation since the economic, comfort, and business are largely determined by dispatch of the airline and business management. The analysis was initiated at node 5 in the FAN, as presented in Figure 4.2. The area marked in blue in Figure 4.2 will be analyzed in the CWR and onwards.

Table 4.1: The Cognitive Work Requirements (CWRs) and Information / Relationship Resources (IRRs) of the goal-process node 5 with the goal: "Protect passenger & crew health."

CWR G5.1	Monitor/predict the passengers health now and over time.
IRR G5.1.1	Present the conditions passengers and crew are exposed to now and over time, together with the human limitations and exposure limits, such as temperature, partial pressure, oxygen, accelerations, or air quality.
IRR G5.1.2	Present when health is endangered along the flight path.
CWR G5.2	Select counter measures; change flight plan, use protective systems, or request/apply assistance.
IRR G5.2.1	Present availability of counter measures and effectiveness.
CWR P5.1	Determine the (cause) destructor of the people's health.
IRR P5.1.1	Present hazardous causes inside the cabin now and over time.
CWR P5.2	Prevent harm by using protective systems (e.g., seat belts, emergency oxygen, ventilation, cooling, heating, evacuation).
IRR P5.2.1	Present availability and status of protective systems
CWR P5.3	Decide if medical assistance (onboard or at hospital) is required, and apply if needed.

Table 4.1 Continued: The Cognitive Work Requirements (CWRs) and Information / Relationship Resources (IRRs) of the goal-process node 5 with the goal: "Protect passenger & crew health."

IRR P5.3.1	Provide an expert advice (medical doctor).
IRR P5.3.2	Deliver medical records to experts of harmed passenger(s).
IRR P5.3.3	Present location of the nearest (available) medical assistance.
CWR G5.4	Prevent harm caused by damage to the plane, such as collisions, or fire.

Table 4.2: The Cognitive Work Requirements (CWRs) and Information / Relationship Resources (IRRs) of the goal-process node 7 with the goal: "Maximize system health & aircraft capabilities."

CWR G7.1	Monitor if system health is, or will become, unsatisfactory for sustained flight.
IRR G7.1.1	Present system capabilities, now and over time. Present if capabilities are lost, or close to being lost. Indicate what parts of the flight are affected.
IRR G7.1.2	Present manufacture's or maintenance advice, such as "Land asap."
CWR G7.2	Select counter measures; change flight plan (divert), use protective systems, reconfigure systems, or request/apply maintenance.
IRR G7.2.1	Present availability of counter measures.
CWR P7.1	Determine the cause (destructor) of the lost capability.
CWR P7.2	Determine what functionality can be recovered.
IRR P7.2.1	Present recommended procedure(s) to restore, or preserve system functionality. Present an overview of functionalities that can be restored.
CWR P7.3	Stay on a safe path in a safe space.
IRR G7.3.1	See node 8 – 13 in Figure 4.2.
CWR P7.4	Decide if an immediate landing is needed.
IRR P7.4.1	Indicate if th airplane will become uncontrollable, or systems will deteriorate rapidly in the near future.
CWR P7.5	Determine if plane is still airworthy, or requires maintenance, for the next flight.
IRR P7.5.1	Present where & when the plane can get serviced and how long this would take.
IRR P7.5.2	Present if maintenance inspection is required, and if Miminum Equipment List (MEL) is still satisfied.

Table 4.3: The Cognitive Work Requirements (CWRs) and Information / Relationship Resources (IRRs) of the goal-process node 8 with the goal: "Achieve Satisfactory Path for Payload."

CWR G8.1	Select a gate and ground handling services, to maneuver the payload safely, time efficient, cost efficient, and comfortable to the aimed destination.
IRR G8.1.1	Present status of available and required services or facilities, processes, and how much time they take.
IRR G8.1.2	Present relative movement and distance from docking site.

4

Table 4.3 Continued: The Cognitive Work Requirements (CWRs) and Information / Relationship Resources (IRRs) of the goal-process node 8 with the goal: "Achieve Satisfactory Path for Payload."

IRR G8.1.3	Present not satisfactory spaces in terms of safety, costs, schedule, compliance, comfort. See node 9 in Figure 4.2.
IRR G8.1.4	Present status of usable access points, such as air bridges.
IRR G8.1.5	Present turn-around time.

Table 4.4: The Cognitive Work Requirements (CWRs) and Information / Relationship Resources (IRRs) of the goal-process node 9 with the goal: "Maximize Payload Space."

CWR G9.1	Monitor suitability of gates.
IRR G9.1.1	Present availability of gates (i.e., time slot), and the cause of unavailable gates.
IRR G9.1.2	Present safe gates, and the cause of not safe gates.
IRR G9.1.3	Present compliant gates, and the cause of not compliant gates.
IRR G9.1.4	Present the comfort level of gates, and the cause of not comfortable gates.
IRR G9.1.5	Present many passengers will make connections, and how many not.
IRR G9.1.6	Present costs of gate service.
IRR G9.1.7	Present gate at planned destination.
CWR P1.2	Request permission, or facilities services to open up gates.
IRR P1.2.1	Present availability of facilities (such as maintenance, medical assistance, accommodations, connections, customs).
CWR P1.3	Select a gate that is reachable with a satisfactory ground path.
IRR P1.3.1	See node 10 – 13.

Table 4.5: The Cognitive Work Requirements (CWRs) and Information / Relationship Resources (IRRs) of the goal-process node 10 with the goal: "Achieve Satisfactory Ground Path."

CWR G10.1	Determine what paths are achievable with the performance of the plane.
IRR G10.1.1	Present possible paths as a result of the system capabilities and environmental conditions.
IRR G10.1.2	Present impact of different system configurations (achieving maximum and minimum performance).
CWR G10.2	Select from the achievable paths a safe, cost-effective, compliant, time-effective, and comfortable ground path.
IRR G10.2.1	Present if planned path is safe and within the safe ground space.
IRR G10.2.2	Present if the planned path is as budgeted.
IRR G10.2.3	Present at what time the plane will arrive at the planned gate.
IRR G10.2.4	Present if planned path is an authorized path by ATC and within the authorized ground space.
CWR P10.1	Request push-back or towing.
IRR P10.1.1	Present status and availability of towing or push back.

Table 4.6: The Cognitive Work Requirements (CWRs) and Information / Relationship Resources (IRRs) of the goal-process node 11 with the goal: "Maximize Ground Space."

CWR G11.1	Monitor suitability of runways, taxiways, and aprons.
IRR G11.1.1	Present availability of runways, taxiways, and aprons (i.e., time slot), and the cause why runways, taxiways, and aprons are unavailable.
IRR G11.1.2	Present safe runways, taxiways, and aprons, and the cause why runways, taxiways, and aprons are not safe.
IRR G11.1.3	Present authorized runways, taxiways, and aprons, and the cause why runways, taxiways, and aprons are not compliant.
IRR G11.1.4	Present costs of using runways, taxiways, and aprons and if this is within budget.
IRR G11.1.5	Present runways, taxiways, and aprons at planned destination.
CWR P11.2	Request permission to cater ground spaces.
CWR P11.3	Select a runway, taxiway, and apron that is reachable with a satisfactory air path.
IRR P11.3.1	See node 12 – 13.

Table 4.7: The Cognitive Work Requirements (CWRs) and Information / Relationship Resources (IRRs) of the goal-process node 12 with the goal: "Achieve Satisfactory Flight Path."

CWR G12.1	Determine what flight paths are achievable with the performance of the airplane.
IRR G12.1.1	Present the possible paths as a result of the system capabilities and environmental conditions.
IRR G12.1.2	The impact of different system configurations (achieving maximum and minimum performance).
CWR G12.2	Select from the achievable paths a safe, cost-effective, compliant, time-effective, and comfortable flight path.
IRR G12.2.1	Present if the planned path is safe and within the safe airspace.
IRR G12.2.2	Present if the planned path is as budgeted.
IRR G12.2.3	Present at what time the airplane is expected to arrive at the planned gate. Together with the earliest time possible.
IRR G12.2.4	Present if planned path is an authorized path by ATC and within the authorized ground space.

Table 4.8: The Cognitive Work Requirements (CWRs) and Information / Relationship Resources (IRRs) of the goal-process node 13 with the goal: "Maximize Air Space."

CWR G13.1	Monitor suitability of airspaces.
IRR G13.1.1	Present availability of airspaces including temporal aspects, such as time slots, and the causes why airspaces are unavailable.
IRR G13.1.2	Present safe airspaces, and the causes why airspaces are not safe.
IRR G13.1.3	Present authorized airspaces, and the causes why airspaces are not compliant.

Table 4.8 Continued: The Cognitive Work Requirements (CWRs) and Information / Relationship Resources (IRRs) of the goal-process node 13 with the goal: "Maximize Air Space."

IRR G13.1.4	Present costs of using airspaces and wether this is within budget.
CWR P13.2	Request permission to open up airspaces.

4.6. Representation Requirements

The work domain captures many of elements that are spread over various actors, automated systems, and displays. The FAN as presented in Figure 4.2 and the CWRs, and IRRs presented in the previously presented tables can form the basis for many applications such as: dispatchers, flight planners, ground operators, and of course pilots. Moreover, the earlier presented IRRs are of such a variety that it would be practically impossible that one display element embodies all of these requirements. Therefore, the information requirements must be scoped and divided among display elements. This scoping depends on the intended goal of the display element and the subset of requirements that was analyzed with the FAN, CWRs, and IRRs.

4

In this project, the focus is placed on in-flight flight plan management in a scenario where system management tasks are largely performed by the automation. The system management tasks are allocated to automation, however, the implications on the flight plan still need to be communicated to the pilot. Therefore, the decision-making support display should integrate all effects on the operation and transform this information to flight plan relevant information. For now, the focus is placed on evaluation and not (yet) on execution. Furthermore, all impacts that are related to comfort, schedule, and economics are disregarded, for now. The focus will be put on safety and compliance. The Representation Design Requirement (RDR) are presented in Table 4.9.

Table 4.9: The Representation Design Requirements (RDRs) for the flight plan management support

Context	Displays should integrate all impacts on safety and compliance on the operation and transform this information to flight plan relevant information, such that the pilot can evaluate the impact of in-flight disruptions.
CWR G5.1	
IRR G5.1.2	Present when health is endangered along the flight path.
CWR G7.1	
IRR G7.1.1	Present system capabilities, now and over time. Present if capabilities are lost, or close to being lost. Indicate what parts of the flight are affected.
IRR G7.1.2	Present manufactures or maintenance advice, such as "Land asap."
CWR P7.2	
IRR P7.2.1	Present recommended procedure(s) to restore, or contain systems. As well as, an overview of functionalities that can be restored
RDR 1	Provide the status of the system capabilities, how they are affected, and how they are impacting the flight plan. Show the recommended actions to restore or contain functionality losses.

Table 4.9 Continued: The Representation Design Requirements (RDRs) for the flight plan management support

RDR 2	Provide an indication when passenger health and system health is endangered.
CWR G9.1	
IRR G9.1.1	Present availability of gates (i.e., time slot), and the cause of unavailable gates.
IRR G9.1.2	Present safe gates, and the cause of not safe gates.
IRR G9.1.3	Present compliant gates, and the cause of not compliant gates.
RDR 3	Provide an indication of the availability, safety, and compliance of the landing sites in relation to the operation.
CWR G10.1	
IRR G10.1.1	Present possible paths as a result of the system capabilities and environmental conditions.
CWR G10.2	
IRR G10.2.1	Present if the planned path is safe and within the safe ground space.
CWR G11.1	
IRR G11.1.1	Present availability of runways, taxiways, and aprons (i.e., time slot), and the cause why runways, taxiways, and aprons are unavailable.
IRR G11.1.2	Present safe runways, taxiways, and aprons, and the cause why runways, taxiways, and aprons are not safe.
RDR 4	Provide an indication if runways are available, and provide sufficient length to land safely with the current conditions (environmental conditions and system capability).
CWR G12.1	Determine what flight paths are achievable with the performance of the airplane.
IRR G12.1.1	Present the possible paths as a result of the system capabilities and environmental conditions.
CWR G12.2	
IRR G12.2.1	Present if the planned path is safe and within the safe airspace.
CWR G13.1	
IRR G13.1.1	Present availability of airspaces including temporal aspects, such as time slots, and the causes why airspaces are unavailable.
IRR G13.1.2	Present safe airspaces, and the causes why airspaces are not safe.
RDR 5	Visualize the flight plan and airspaces resulting from the capabilities/performance of the plane and the environmental conditions in the horizontal, vertical, time, and velocity domain.

4

4.7. Discussion

The benefit of the ACWA method is that an external mental model is created based on a normative work domain model that, if done properly, corresponds with the operator's mental model. This mental model is used to solve problems and make decisions. The model embodies many elements. These elements have complex relations, which may sometimes influence each other in a circular manner. The ACWA method allows for such mappings, due to its less restrictive nature compared to other methods.

However, the real power of this technique is that abstract elements can be extracted that can be used to explain many processes. The main abstract elements for air transportation are space and path. These elements change over time. Spaces are created and destroyed; they become possible or impossible; they become authorized or restricted. This creation of spaces, or 'opening the world' is dependent on the goal (safety, schedule, cost, compliance, and comfort). The pilot has to choose which spaces can be crossed and which not, depending on the intended operation. Another important note is that spaces are influenced by time since some spaces are effective for a certain time period.

The abstract element of path has similar characteristics as the space element. Paths are created with the performance of the aircraft. For example, a helicopter has an entire different set of created paths than an aircraft. An aircraft requires airflow over the wings to generate lift, which results in a minimum speed; but also, a maximum speed exists, which is often the result of the propulsion performance of the plane and structural capability of the plane. Each aircraft is different and can create different paths. Restrictions on paths are also put in place, such as speed restrictions. The 'width' of the path is the result of the position determining system. The human without aid is not very good at estimating the position or altitude, especially if there is no visual contact, so the error is large. The same holds for determining the position of other objects.

The FAN and the subsequently derived requirements capture a wide span of processes. This is the result of the method in which the entire system is described. The FAN can therefore be used for many applications as well as for specific tasks. Further detail can be added if required for the focus area.

The knowledge base provided by the ACWA focused on all aspects of the flight operations in which many actors are involved. Any of the tasks in the FAN and the described CWR are performed by others than the pilots, such as dispatch, maintenance, or operations management. Take for example a dispatcher, who's task is to monitor multiple flights at the same time. Instead of a single flight operation, many flights are being controlled. For this task the ACWA can still be used. The focus is, however, in such case placed on business operations.

Furthermore, some of the prescribed tasks are performed by the pilot. For example, choosing a taxi route or runway is not possible, since this is determined by ATC. The pilot often has simply to accept the clearance on controlled airfields. However, this can change at landing sites where the pilot is responsible for its own ground operations.

The ACWA is intended as an iterative process by Elm & Potter (2003). This entails that the model and requirements can be provided with more or less detail based on the intended use of the tool. One can start of high level and refine the model and requirements where necessary. Additional features on the displays can be added to support the requirements that are not fulfilled yet.

It is important to note that some requirements determined in the CWRs and IRRs are not entirely pragmatic. Some requirements can be considered as a wishlist that can drive new instrumentation or sensor technology. Each of the IRRs need to be assessed to determine if what is required for is also realizable or practical. For example, Table 4.1 describes the CWRs and IRRs to manage passenger health. However, this is quite a difficult aspect to measure with sensors, is privacy sensitive, or compromises comfort. Asking everybody to wear a measurement device, such as heart-rate monitor, or a thermometer, would be onerous. But in this can other passengers or cabin crew members can be appointed with this task. However, for the pilots this can become a requirement for single crew operations, since there will not be another person to monitor the pilot's health. The identified requirements from the ACWA can thus be used as basis for task allocation and the development of sensors and equipment.

The last step of transforming the RDRs was not described in this study, because this is the more artistic part. Many possibilities exist to visualize these requirements. Skill is needed in order to perform this accurately and effective. Knowledge of capabilities of the human operator, such as attention, perception, and of usability is required for this process. The RDRs are translated to a visual form in Chapter 5.

4.8. Conclusions

This study aimed to determine what information needs to be presented by flight-plan-management supports. The focus was put on the pilot in its role as a decision-maker for commercial flight operations. The ACWA provides a structured way to organize this information. High-level goals and abstract elements are found that can be utilized to describe the flight operation and impacts on the flight operations. The main abstract elements of commercial flight operations in this analysis are found to be space and path. Alerting in terms of these elements is according to this analysis an effective way, from a cognitive perspective, to support understanding if the flight plan is still achievable. The 'new' finding from this analysis is that the system capabilities together with environmental conditions should be combined to map spaces and paths. Only then does data become goal-oriented information, relevant for problem solving.

The CWRs, IRRs, RDRs can be used to design the intended support. However, the applications are broader than one display. The FAN can be used the design a variety of tasks, jobs, and automated systems. The CWRs, IRRs, RDRs can be extended if the task requires to. This analysis can be seen as a holistic approach to map the work done during commercial flight operations. Adaptations of the FAN and CWRs to other commercial transportation domains is feasible, such as automotive, shipping.

References

Bennett, K.B. and Flach, J. (2011). *Display and Interface Design: Subtle Science, Exact Art*. CRC Press.

Billings, C. E. (1996). *Human-Centered Aviation Automation: Principles and Guidelines*. Technical report.

Burian, B. K., Barshi, I., & Dismukes, R. K. (2005). The Challenge of Aviation Emergency and Abnormal Situations. *NASA Technical Memorandum*, (June), 1–21.

De Filippis, L., Gaia, E., Guglieri, G., Re, M., & Ricco, C. (2014). Cognitive based design of a human machine interface for telenavigation of a space rover. *Journal of Aerospace Technology and Management*, 6(4), 415–430.

Elm, W. C. & Potter, S. S. (2003). Applied Cognitive Work Analysis: a Pragmatic Methodology for Designing Revolutionary Cognitive Affordances. *Cognitive Task Analysis*.

Gavish, I. & Brenner, B. (2011). Air travel and the risk of thromboembolism. *Internal and Emergency Medicine*, 6(2), 113–116.

Lind, M. (1994). Modeling goals and functions of complex industrial plants. *Applied Artificial Intelligence*, 8(2), 259–283.

McIlroy, R. C. & Stanton, N. A. (2015). Ecological Interface Design Two Decades On: Whatever Happened to the SRK Taxonomy? 45(2), 145–163.

Mondragon Solis, F. A. & O'Brien, W. J. (2011). Using Applied Cognitive Work Analysis for a Superintendent to Examine Technology-Supported Learning Objectives in Field Supervision Education. *Computing in Civil Engineering*, (pp. 194–201).

Norman, D. A. (2013). *The Design of Everyday Things*. New York: Basic Books, revised edition.

Potter, S. S., Gualtieri, J. W., & Elm, W. C. (2003). Case studies: Applied Cognitive Work Analysis in the Design of Innovative Decision Support. *Handbook of Cognitive Task Design*, (September 2014), 653 – 678.

Rasmussen, J. (1983). Skills, Rules, and Knowledge; Signals, Signs, and Symbols, and Other Distinctions in Human Performance Models. *IEEE Transactions on Systems, Man and Cybernetics*, SMC-13(3), 257–266.

Rasmussen, J., Pejtersen, A., & Goodstein, L. (1994). Cognitive Systems Engineering. *"Ergonomics: The history and scope of human factors"*, (October).

Reitsma, J., Fucke, L., Borst, C., & van Paassen, M. (2017). Taking a Closer Look at Flight Crew Handling of Complex Failures – Ten Case Studies. In *19th International Symposium on Aviation Psychology (ISAP 2017)* Dayton.

Reitsma, J., Van Paassen, M., & Mulder, M. (2019). Methodology Comparison for Designing a Decision-making Support System. In *IFAC-PapersOnLine*, volume 52.

4

Vicente, K. J. & Rasmussen, J. (1992). Ecological Interface Design: Theoretical Foundations. *IEEE Transactions on Systems, Man, and Cybernetics*, 22(4), 589–606.

Woods, D. D. & Hollnagel, E. (1987). Mapping Cognitive Demands in Complex Problem-Solving Worlds. *International Journal of Man-Machine Studies*, 26(2), 257–275.

5

Design of an Operational Alerting Support

What would the flight deck look like if it would be focused on supporting operational decision making?

Automation is sometimes referred to as a double-edged sword, it can reduce workload, as was found in Chapter 3, but at the same time it can adversely affect situation awareness. In Chapter 4, a Applied Cognitive Work Analysis (ACWA) was conducted, which provides an objective set of requirements for the content of a user interface to support flight plan management.

In this chapter, the predefined requirements are translated into a visual form. The main ideas behind the operational alerting interface are explained and each display will be discussed individually. In total, five displays were (re)designed to support flight plan management.

5.1. Introduction

The main responsibility of the human pilot is to manage and make decisions regarding the remainder of the flight, as was discussed in Chapter 1 and 2. Hence, it would be expected that flight decks currently in service would provide seamless flight-plan management support (both tactical and strategical). In reality, predicting impacts on the remainder of the flight can be a taxing task for flight crews (Reitsma et al., 2017). This study was initiated to explore ways to improve flight-plan management supports.

This aim is also relevant in the light of recent development regarding automated systems. System management tasks are increasingly automated. Although automation can reduce workload, increased levels of automation may reduce overall situation awareness (Lee et al., 2017). Pilots do not necessarily have to be aware of every technical detail of the system (e.g., status of temperatures and pressures), but pilots should be at always aware of the impacts on the flight plan caused by a changed system state, in particular, when an automated system reconfigures without human intervention. These impacts need to be communicated —in an effective way— to the pilot such that s/he can make well-informed decisions. This study proposes a redesign of flight-deck displays to enhance decision-making performance, by visualizing impacts on the flight plan, and placing the primary focus of the supports on flight-plan management.

Interfaces can be designed in many ways. However, human-machine systems should be designed such that they are adapted to the humans' capabilities (both physical and cognitive) rather than requiring the human to train for and adapt to a system's peculiarities. An Applied Cognitive Work Analysis (ACWA) was performed (see Chapter 4) to determine what information needs to be presented to effectively support the in-flight decision-making process of commercial pilots.

The ACWA is a stepwise process, which starts by mapping the work domain according to two key principles. First, the work domain is mapped to promote goal-oriented reasoning. In this way both bottom-up and top-down problem solving is supported. Second, the analysis uses abstraction to cope with the complexity of the work domain. So, information is organized and summarized into easy processable elements, thus reducing the overall cognitive demand.

Although the ACWA presented in Chapter 4 resulted into an objective set of Representation Design Requirements (RDRs), the actual transformation to a visual form was left untouched. In this chapter, the final step of the ACWA is performed, which is transforming the RDRs into Presentation Design Concepts (PDCs) (i.e., the actual visual form). It is important to mention is that the transformation to a visual form is a creative process. No absolute truth exists and many outcomes are viable. And for multiple outcomes the predefined requirements can be met. This chapter shows just one possible outcome. The RDRs —as presented in Chapter 4— used as the starting point for this study, which are summarized in the following section.

5.2. Representation Design Requirements

Table 5.1 shows the RDRs extracted from the full list of requirements performed in Chapter 4. The requirements related to economic and comfort goals are left out. Those are out of the scope for this initial concept design. Furthermore, the Cognitive Work

Table 5.1: The Representation Design Requirements (RDRs) for the flight plan management support

Context	Displays should integrate all impacts on safety and compliance on the operation and transform this information to flight plan relevant information, such that the pilot can evaluate the impact of in-flight disruptions.
RDR 1	Provide the status of the system capabilities, how they are affected, and how they are impacting the flight plan. Show the recommended actions to restore or contain functionality losses.
RDR 2	Provide an indication when passenger health and system health is endangered.
RDR 3	Provide an indication of the availability, safety, and compliance of the landing sites in relation to the operation.
RDR 4	Provide an indication if runways are available, and provide sufficient length to land safely with the current conditions (environment and system capability).
RDR 5	Visualize the flight plan and airspaces resulting from the capabilities/performance of the plane and the environmental conditions in the horizontal, vertical, time, and velocity domain.

Requirements (CWRs) and Information / Relationship Resources (IRRs) are left out for simplicity, but they can be found in Chapter 4, Table 4.9. These requirements will be the theoretical (human-centered design) foundation for the displays and will be referred to in the upcoming sections.

5.3. Visual Form

5.3.1. Design Overview

The design process initiates with determining the global layout of the display elements (i.e., the number and position of the displays). This is an iterative process, as it depends on the RDRs, the designer view, potential re-usable display elements and available display real estate. In this case, the available displays were based on the Boeing 787 flight-deck architecture, which global layout is shown in Figure 5.1. Previous research is used to visualize some of the RDRs (Van Paassen et al., 2018), in other cases new solutions had to be found.

As was mentioned earlier, the focus of the flight-deck support was to present impacts on the operation (i.e., the flight plan). A flight plan is subjected to horizontal, vertical, speed, and time constraints within the abstract elements of space and path. The displays needed to represent such spaces and paths across all these aspects. This led to three main display elements, the Horizontal Situation Display (HSD), the Vertical Situation Display (VSD), and the Time and Velocity Situation Display (TVSD). The current Navigation Display (ND) is used as a template canvas to which features prescribed by the requirements from the ACWA are added. This also holds for the VSD, which already exist on the state-of-the-art displays. On the other hand, the TVSD is not existing on the current flightdeck, but is used as a planning tool in other domains such as rail traffic management (Tufte, 1990) and air traffic control (Klomp et al., 2019; Van Der Eijk et al., 2012). These various design templates are used to develop a TVSD for the flight deck.

The three displays —HSD, VSD, and TVSD— work together and show the overview of the flight plan, constraints, and capabilities of the aircraft from all aspects of the flight plan. The multiple display elements are displayed in such a way that the visual momentum is supported (Lee et al., 2017). For example, the scales are connected to show the same effects on space and path on all displays.

Impacts are caused by both environmental and internal conditions (i.e., the systems). Awareness of the system capabilities is key to predict impacts on flight. Hence, the implications caused by the system needed to be presented as well (**RDR 1**), resulting into the Functional System Status Display (FSSD). This status overview presents the status of the aircraft in a functional way. An example of the is presented by Mumaw et al. (2018). A change in capability does not necessary result into an impact on the flight plan. For example, the lost capability to fly a precision approach path with a ILS CAT III is not a problem if this approach was not initially planned, or if the weather conditions do not require it. The pilot needs an overview to determine what caused the impact, and to predict what future operations are possible.

Furthermore, **RDR 1** prescribes that the displays should show an indication of the impacts on the flight plan. This can be done in many ways; either by presenting it in the map as labels, or to have a dedicated space to summarize the impacts. However, for this concept it was chosen to present impacts in a central location, as a list of impacts. This would ensure scrolling would not be needed. These list items can be seen as tasks that need to be resolved, or fixed. This 'fixing' of the flight plan can either be done by replanning, by reconfiguring the system, or by communicating to change the external conditions (e.g., by asking for permission). The impacts can also be seen as alerts since they are alerting for operational impacts. Therefore, the impacts are further referred to as **operational alerts**.

Besides the task of fixing the flight plan, the systems need to be configured to avoid further deteriorations, or restore functionality in case of a malfunction, or deliver the demanded capability. Procedures are available that present the recommended actions to restore or contain functionality losses. These actions are presented together with the operational alerts. The pilots have therefore good overview of the malfunctions and the consequential impacts. Containing malfunctions by isolating and reconfiguring the systems has often the first priority after which the flight plan will be changed. All these items are presented in the newly proposed Alerting and Task Display (ATD).

So, in total five views are implemented, which are: HSD, VSD, TVSD, FSSD, and ATD. The locations can be changed, since Multiple Function Displays (MFDs) allow for multiple locations of the display element. However, for this initial concept this is not considered.

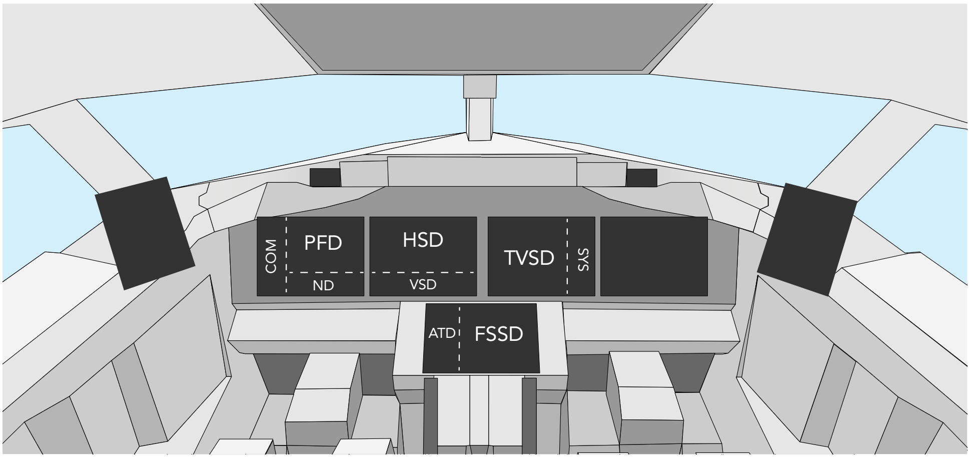


Figure 5.1: The global layout of the proposed concept flight deck supports where the HSD, VSD, TVSD, FSSD, ATD are newly introduced displays.

5.3.2. Horizontal situation display

The HSD is arguably the most obvious display to represent the flight plan and operating space. It embodies all of the requirements, **RDR 1 – 5**. The HSD shows spaces and paths for the flight, ground, and passenger domain, the impacts on the flight, and where safety is compromised. The HSD is presented in Figure 5.2.

Flight Path and Airspaces

Figure 5.2 shows a non-normal case in which multiple electrical systems are failed, such as the yaw damper, window heating and pitot heating systems. These result into issues in controllability, sensing, and visibility when turbulence and icing conditions are encountered, respectively. In this scenario, these turbulence and icing conditions are present, hence, the area in which they occur is color coded with amber. These spaces are now a threat for the safety of the flight. The current path is crossing these spaces, which are highlighted with amber parts of the flight path. These amber parts of the path correspond to an operational alert as depicted on the ATD, where more information and guidance for resolution is provided.

Presenting icing or turbulence areas is not new, however, adding context in terms of the flight plan (crossed, or not) and the system capabilities (protection systems available on, or not) is. This context makes information relevant since the hazards are pointed out with respect to the intended plan. The capabilities of the aircraft are important in these considerations since these conditions can be managed with normal functioning protection systems and would therefore be less severe and no longer be a threat.

System functionalities can ‘open’ or ‘close’ possible spaces. For example, Reduced Vertical Separation Minima (RVSM) airspaces require a set of systems to function properly in order to guarantee separation. If one of these system would fail, or is switched off, using RVSM airspace would not be authorized. The space would then be marked as ‘closed’ (i.e., amber or white depending on the severity). Some action needs to be

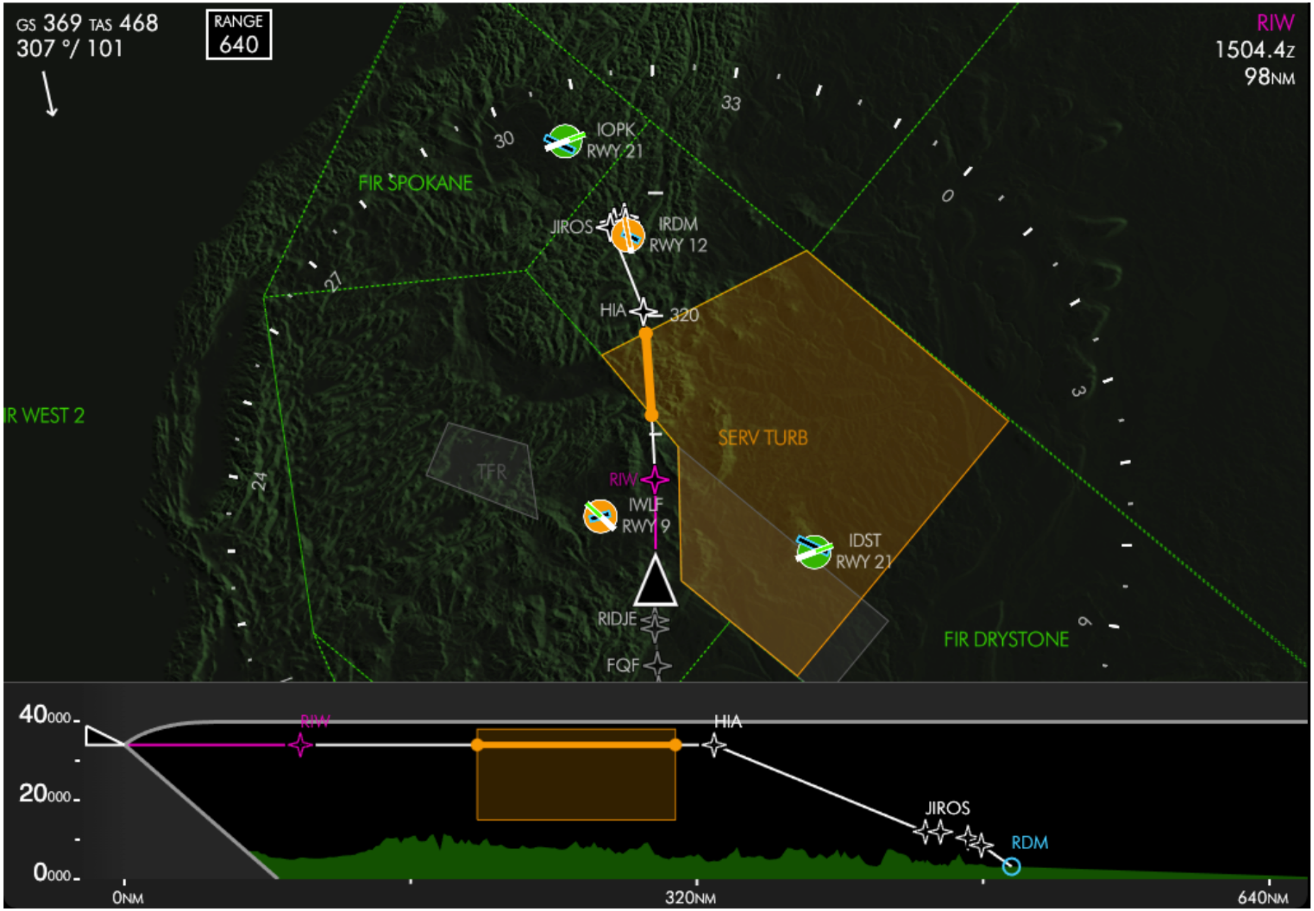
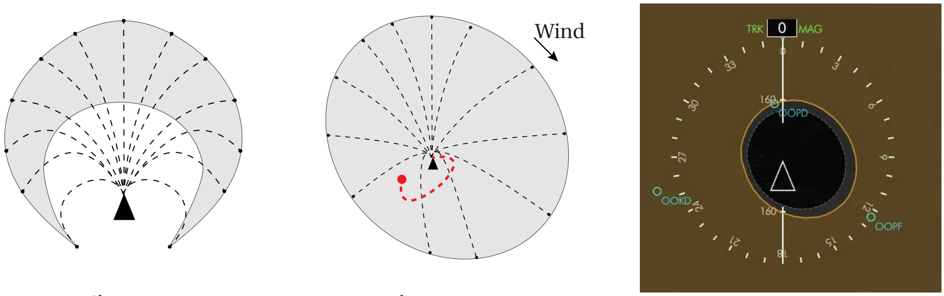


Figure 5.2: The Horizontal Situation Display (HSD) and Vertical Situation Display (VSD) presented in one display, top and bottom respectively. The HSD presents the paths and spaces for flight operation, ground operation, and passenger handling. Below, the VSD presents where spaces are crossed along the flight path from the vertical perspective. The presented path is a projection of the path presented in the HSD.

taken to avoid the risk of collisions. For example, changing course or altitude to exit this space, or asking permission from ATC to continue. This mechanism of opening and closing spaces is a core principle behind the HSD.



a) Short term Performance Envelope

b) Long Term Performance Envelope

c) Display Concept

Figure 5.3: Horizontal maneuvering capabilities for short and long term. Borst et al. (2008) and Rijndorp et al. (2021) present a similar visual representation of other uses cases, such as engine failures and flight envelope limitations.

The horizontal display presents the top-down view of the planned path. **RDR 5** states that the capabilities of the plan should be presented. This translates to where the plane can reach on the horizontal plane. In theory, each point would be possible with a series of turns and straights. However, the reachable positions depend on speed and time. Time is limited, due to the amount of fuel on board. The usage of fuel depends on the performance of the airplane. Presenting the capabilities in the horizontal plane can create some confusion due to the large number of possibilities to construct a path.

However, one could indicate the range of the aircraft as an envelope, as is presented in Figure 5.3. Figure 5.3 (a) presents a short-term envelope, just like (Borst et al., 2008; Rijndorp et al., 2021). Here, the turn rate, and velocities determine the size of the envelope. If more time is considered, more locations can be reached. A long term envelope is presented in Figure 5.3 b). The outer boundaries can be reached with a specific set of maneuvers. The boundaries of the envelope are showing the maximum reachable distance. This can be reached with several strategies, deviating from this specific strategy (different turns, or different speeds) will result into not reaching the boundary. This is indicated in Figure 5.3 (b) with the red line. It can therefore be dangerous if one would rely too much on the envelope, a slight variation will make the path infeasible. This is why it is not included of the HSD, and transferred to the TVSD, which will be presented later. The aircraft capabilities and the environmental conditions, such as wind, produce an envelope presented by 5.3 (c). This allows the pilot to determine which airports are out of reach and which are not.

Ground and Payload Path and Spaces

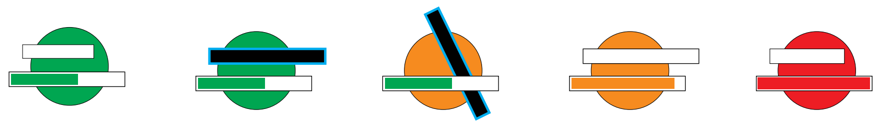
The HSD furthermore embodies **RDR 3**, **RDR 4**. Aircraft are limited by airports; they can only land at dedicated places. However, in emergencies the pilot needs to be creative (e.g., US Airways Flight 1549 accident). These landing sites are either suitable or unsuitable, depending on the ground operations and passenger maneuvering capability.

RDR 3 states that an indication should be provided if a landing site is available, safe, and compliant with regards to the operation. The facilities can be unavailable, or passengers have visa restrictions, or deplaning might be dangerous. In the HSD this is depicted with the symbols presented in Figure 5.4. The color of the circle behind the runway symbology provides an indication whether operation to that airport is suitable, or if some limitations are present, making it impossible to achieve some or all goals.

Next, **RDR 4** states that the feasibility of the ground operations needs to be presented, which is done by the symbols presented in Figure 5.4. The available runways are presented with a white background, which stand out on the black background on the flight-deck displays. The runway orientation is similar to the real world and will be re-drawn based on the aircraft orientation. This is chosen based on the *principle of pictorial realism* and *principle of the moving part* (Lee et al., 2017). This represents the available ground maneuvering space. If a runway becomes unavailable, the runway is marked with a black background and with a cyan border. Unavailable runways are determined not only from the status of the runways, but also considers the match between the aircraft and the runway showing whether this particular aircraft can land at that runway. A mismatch between ACN and PCN is another measure that can result into an unavailable runway, since heavier aircraft can only land on specially engineered runways.

The length of the runway is also presented in the symbols; each symbol presents a mini-map layout of the airport, again, to support the creation of an accurate mental model of the operating world. The taxiways and aprons are not (yet) presented, but this can be done in a similar fashion as the current airport map on Boeing aircraft or the On-Board Airport Navigation System (OANS) on Airbus aircraft.

Besides the availability, the active runway with the estimated landing distance required is presented with a green, amber, or red bar. The color of the bar indicates if an overrun is predicted. Green stands for sufficient landing performance, amber indicates that the margin between the landing distance required and the landing distance available is less than 500 meters, and red indicates an overrun. The calculation is performed based on the environmental conditions and the planned landing configuration. It is assumed that external information on the runway conditions is available.



a) Suitable airport with two available runways

b) Suitable airport with one available runway

c) Non-suitable airport from the passengers perspective

d) Airport where landing performance is critical

e) Airport where landing performance is unsufficient

Figure 5.4: Example of airport icons presenting ground maneuvering space, and passenger space.

5.3.3. Vertical situation display

RDR 5 describes that it is necessary to visualize the flight plan and airspace properties resulting from the 'affordances' of the aircraft and the constraints for the vertical domain. This aspect of the flight plan is presented by the VSD (presented in Figure 5.2). The VSD depicts the vertical flight path as a projection of the flight plan as presented in the HSD. The climb and descent performance are visualized in grey. The black part in Figure 5.2 is the available operating space, and the grey part is unachievable. The path is constrained by spaces along the way. A physical constraint is the terrain, which is presented with green in the example (i.e., in line with the EGPWS way of showing terrain). However, other types of spaces are also present. They correspond with the spaces presented in the HSD. The pilot can observe where the path is crossing hazardous spaces, and can consequentially create a solution; for example descend or ascend. If that is still not possible, a solution could be to modify the horizontal track.

The ascent and descent limits are based on the current configuration of plane. The ceiling is determined by the excess thrust, and the descent rate is limited, to not exceeding the maximum operating limit speed (V_{MO}). The descent rate will be increased by extending the speed brakes, for example. So, the indications will be dynamic and based on the current configuration and environmental conditions.

Margins are added in the form of Minimum Sector Altitudes (MSAs), or Minimum Obstacle Clearance Altitude (MOCA), to avoid collisions with physical space (terrain). These are not yet included in the concept, but would provide an excellent example of a compliant space —as was investigated by Comans (2017). It is possible to enter this space since it provides 1000ft obstacle clearance. However, these spaces are introduced to provide a margin in case the altitude measurement is less accurate (e.g., when conditions are deviating from the standard atmosphere). Flying lower than 1000ft from the terrain will mean that air laws are violated, and consequences for the pilot or company are expected.

This display is predicted to be very useful in abnormal situations where altitude is critical, such as one-engine operation, extended gear operation, cabin depressurization in proximity to terrain. The information on the VSD can provide that essential insight. Furthermore, the cleared flight level can also be presented in the future (this is not yet implemented in this initial version).

The idea of presenting the climb performance of the aircraft in relation with the terrain on a tactile time-scale was first introduced and developed by Borst (2009) and later extended for regulatory constraints by Comans (2017). This VSD concept intents to present the capabilities of the aircraft and the operational environment holistically for a longer timescale, such that it can be used for flight planning.

5.3.4. Time-Distance situation display

RDR 5 describes that the flight plan, operational space, and limitations needs to be presented in terms of speed and time. This is what the TVSD depicts. It presents the path as presented on the HSD and the VSD from the time perspective. The TVSD is presented in Figure 5.5.

The TVSD presents distance vertically and time horizontally. This is chosen because it was predicted that it would better fit the natural mapping of users (based on Norman

(2013)). Faster corresponds to 'going up' and rotate counterclockwise; going slower would be down and rotate clockwise. The grey part is limited by the performance of the aircraft. The upper-left area is caused by the maximum speed at which the aircraft can operate, and the lower-right area is caused by the lowest possible speed (stall-speed, or controllability speed). Since the path is presented with respect to distance, all speeds are expressed as ground speeds. The speed envelope depends on the altitude and is narrower at higher altitudes and wider at lower altitudes. The configuration of the aircraft will also impact the envelope, for example, flaps allow for a lower achievable speed, and impose a reduced maximum speed limit. The flaps will make the envelope rotate clockwise.

Airspaces and airports have all an availability in terms of opening hours (i.e., time slots). These can also be presented with the TVSD. The pilot can estimate when s/he will arrive and whether this is sufficient. By slowing down or speeding up a solution can be found. The time is, furthermore, limited by the resources on-board, such as fuel, battery power, emergency oxygen, and fire suppression gasses. The TVSD is a new concept on the flight deck. However, similar concepts are researched by (Riegman, 2018), and presented in (Tufte, 1990, p. 45).

5

5.3.5. Task management display

The actions recommended to follow and to reconfigure the system in case of a failure are presented in the Alerting and Task Display (ATD). They are a simplified version of the checklist as presented in the QRH. The operational notes —stating what systems are inoperative should be considered for the remainder of the flight— are removed, since these are in this concept translated into impacts on the flight plan. The ATD is presented in Figure 5.6.

Besides the 'classical' system management tasks, the operational alerts are presented. They correspond to the amber path sections on the HSD, VSD, and TVSD. They provide the necessary explanation and possible actions to mitigate the issue. A contingency plan can either include, reconfiguration of the systems, changing the flight plan, or contact the outside world. The boxes in the ATD are buttons; the actions can be accessed by tapping them. Figure 5.6 presents an example of a forward cargo compartment fire that needs to be extinguished. When the fire is contained, the pilot can focus on diverting to a nearest suitable airport. In this case, it needs to be within 60 minutes, which is dictated by the plane's fire suppression system capabilities (i.e., based on certification requirements).

Concurrently, the ATD is supporting the function of task management, which is a crucial part of the work of a pilot. In essence, all tasks could be integrated in this list, such that the pilot has a clear overview and can prioritize accordingly. An empty display would mean that all tasks are done. This initial design only presents system management tasks, and flight planning tasks.

5.3.6. System functionality display

RDR 1 and 2 dictate that an overview of the system status should be provided together with what impacts the system implies on the operation. This is what the Functional System Status Display (FSSD) presents. An example of major electrical failure presented

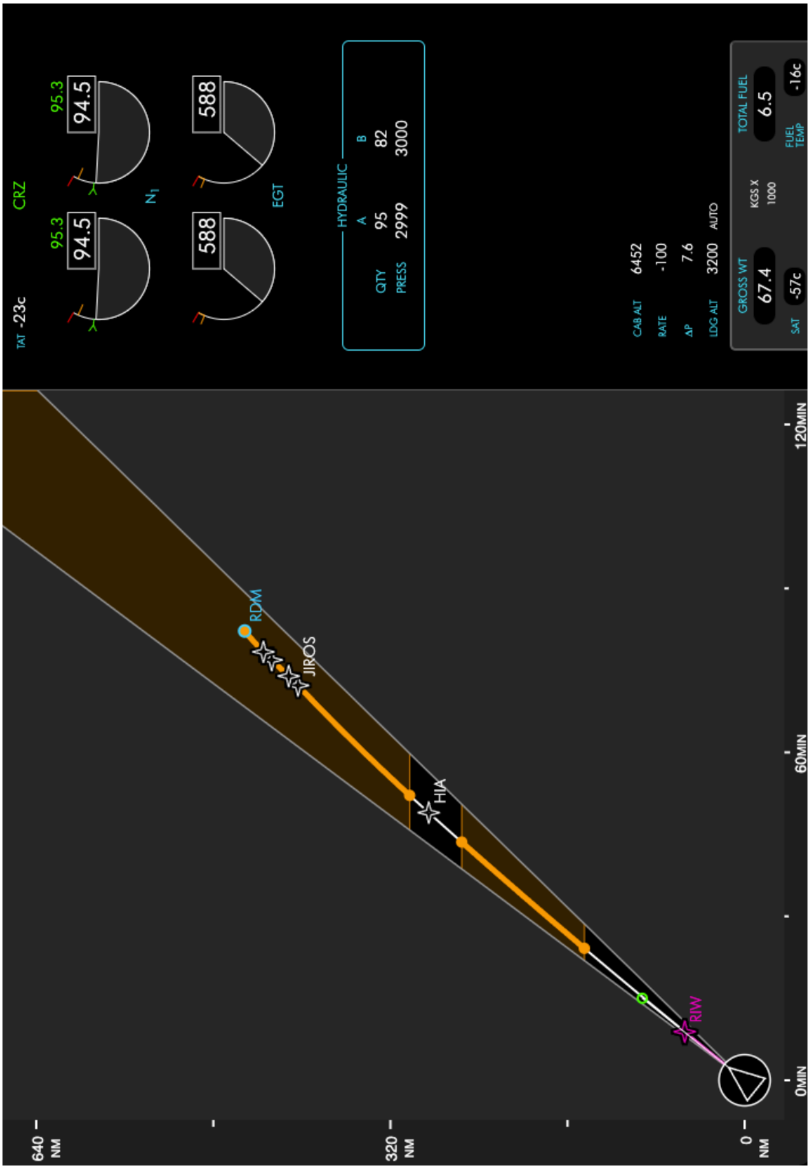
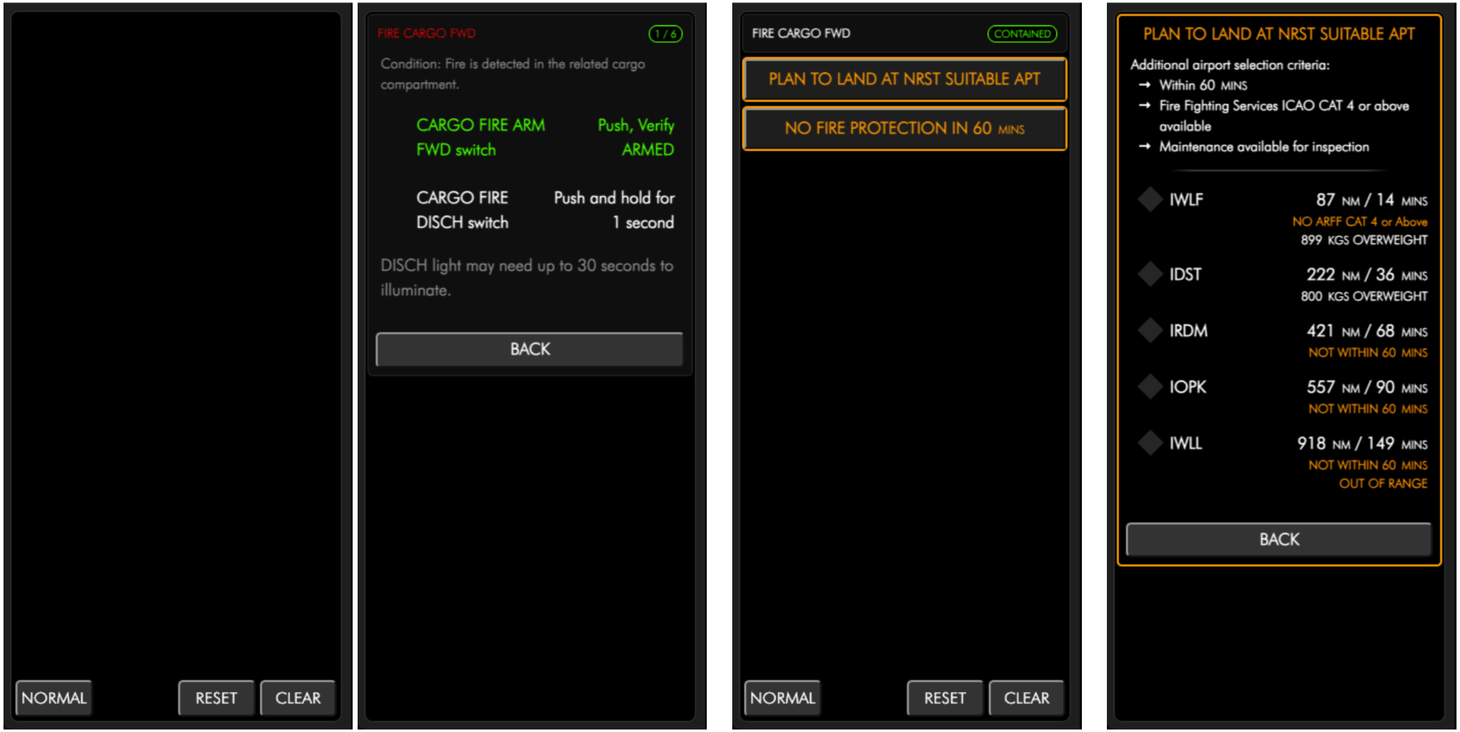


Figure 5.5: An example of the Time and Velocity Situation Display (TVSD) on the left-hand side. Presenting were and when operational alerts occur. Time is presented from left to right and distance from bottom to top. The presented path is a projection of the path presented in the Horizontal Situation Display (HSD).

5



(a) (b) (c) (d)

Figure 5.6: An example of the Alerting and Task Display (ATD) presenting the system management task and operational alerts. The operational alerts correspond to the affected parts of the path on the Horizontal Situation Display (HSD), Vertical Situation Display (VSD), and Time and Velocity Situation Display (TVSD).

5

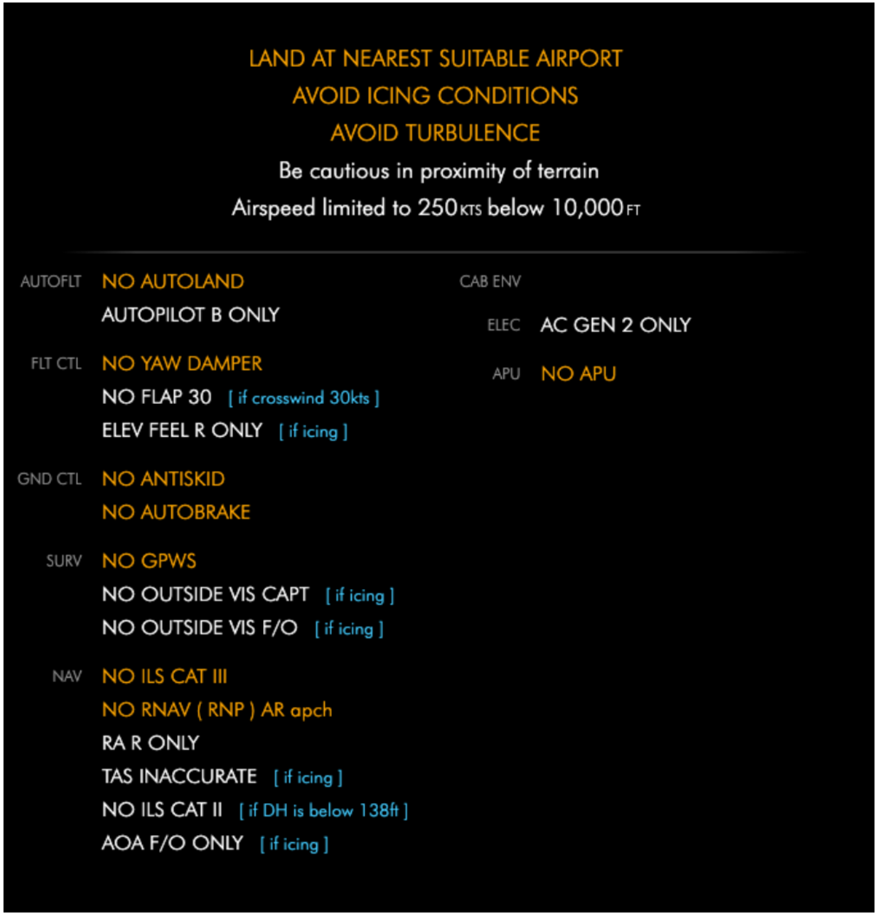


Figure 5.7: An example of the Functional System Status Display (FSSD) for a major electrical failure. It provide a summary on what impacts the system induces on the flight plan, together with a functional overview of the aircraft functionality.

by the FSSD, is shown in Figure 5.7.

The FSSD is divided into two parts. The top part presents the impacts on the operation imposed by the systems capabilities. It presents possible threats that may or may not interfere with the intended flight plan, since this depends on the intended operation and environmental conditions. For instance, a planned approach with clear blue skies and excellent visibility is not affected if ILS CAT III operation is not feasible from a systems perspective. The FSSD will present impacts in such case only for awareness and for planning purposes of future operations.

The lower part of the display shows the system capabilities. This overview presents system status at a functional level rather than the conventional system level. The impact on the functions is only presented if they are lost, or close to being lost. Airplanes are often equipped with redundant systems. Most safety-critical systems are even triple redundant. It would not matter if five out of ten systems are failed. In fact, it would only matter if functions are lost or close to being lost. Furthermore, the pilot should be aware if critical functions rely only on one system. Such information is important to make a well-grounded risk assessment. A lost function is presented as amber starting with 'NO …', and a function that is close to being comprised is presented as white and is depicted with '… ONLY'. Functions can also be lost in specific conditions. Probes, for example, are getting blocked with ice if the heating systems are not functioning, however, only when in icing conditions. This awareness is required to make an informed decision in case the flight plan need to be modified. This condition is presented in cyan in brackets, like [if …].

The functionalities are ordered in groups, which are: Auto flight, Flight control, Ground control, Navigation and position precision, Communication, Surveillance, Crew, Anti-ice, Fire protection, Cabin environment, Passengers, Fuel supply, Hydraulic power, Electric power, Pneumatic power, and Mechanical power (engines and the APU). These are derived from the FAN as presented in Chapter 4. A full list of the proposed messages is presented in Appendix B.

5.4. Discussion

This concept is a first attempt to organize flight deck information in a holistic way such that it supports flight-plan management. Since this is a first iteration, and further improvements are always possible. Experts in usability, perception, or linguistics would most certainly come up with a different result, which is part of the iterative nature of the design process.

More features can be added to provide better support in evaluating impacts on the flight plan, such as the minimum sector altitude, flight-level clearances, hazardous airspace, estimated radio-signal coverages, etc. However, the principle is captured with these display elements and forms a good basis to extend upon.

More support can be added for the planning of a flight when the current flight plan is 'broken'. Standard routes can be added, such as Standard Arrival Routes (STARs), Standard Instrument Departure Routes (SIDs), or escape routes for airlines to leverage on prepared work. These should be assessed on feasibility by the automation based on the system and environmental conditions.

An important issue that needs to be avoided is the potential risk of clutter. Once all spaces and path implications are added, it might be that the amount of information is overloading the pilot even-though abstract elements are introduced to mitigate information overload. These issues can be determined by evaluating the displays under various conditions, as will be done in the next chapter (see Chapter 6).

The HSD and VSD are already implemented on current flight decks. However, the operating spaces and the operational impacts are not included in these conventional displays. The TVSD is, however, entirely new and might be difficult to interpret. It might require users some time to familiarize with this display. Although these displays meet the requirements introduced in Chapter 4, it does not guarantee the best solution regarding usability. Showing the impact on velocity and time with a display, such as the TVSD is only one solution and one that requires some cognitive effort for interpretation. Other solutions to present time and velocity can be found if this approach turns out to be too complicated. Furthermore, the TVSD also consumes a considerate amount of space on the display, which might not be the most effective way of presenting this data.

Recommended flight paths are deliberately not shown, since this can be too leading for the users. This was motivated in Chapter 1 with the discussion on levels of automation. The pilot should be always be engaged with the flight-planning process. Hence, the options need to be generated by the user to keep the user fully engaged.

Although this concept was designed as a display suite on the flight deck, it can also be applied to other concepts of operations. Think for example about the potential of these displays for a remote-controlled solution, or as an operational support for airline dispatchers.

5.5. Conclusions

The RDRs obtained from the ACWA, as presented in Chapter 4 were transformed into a visual form. All RDRs were translated successfully in five display elements. The HSD, VSD, TVSD, FSSD, and ATD. This preliminary concept provides the flexibility to present all capabilities and constraints induced by the system and environment on the operation, respectively. Features can be added or improved if necessary. The usability or styling are possible to be improved upon. However, this first attempt should be evaluated before any further adaptions are made. Next, a usability study will be performed to understand how users work with the concept and most importantly if it will reach the intended design goal, which was to design flight deck interfaces focussed on flight-plan management to enable the pilot to better manage and make more well-informed decisions for the remainder of the flight.

References

Borst, C. (2009). *Ecological Approach to Pilot Terrain Awareness*. PhD thesis, Delft University of Technology.

Borst, C., Sjer, F. A., Mulder, M., Van Paassen, M. M., & Mulder, J. A. (2008). Ecological approach to support pilot terrain awareness after total engine failure. *Journal of Aircraft*, 45(1), 159–171.

Comans, J. (2017). *Procedures in Ecological Information Systems*. PhD thesis.

Klomp, R. E., Riegman, R., Borst, C., Mulder, M., & van Paassen, M. M. (2019). Solution Space Concept: Human-machine Interface for 4D Trajectory Management. *13th USA/Europe Air Traffic Management Research and Development Seminar 2019*, (July).

Lee, J. D., Wickens, C. D., Liu, Y., & Boyle, L. N. (2017). *Designing for People: An introduction to human factors engineering*. CreateSpace.

Mumaw, R. J., Feary, M., Fucke, L., Stewart, M., Ritprasert, R., Popovici, A., & Deshmuk, R. (2018). *Managing Comnplex Airplane System Failures through a Structured Assessment of Airplane Capabilities*. Technical Report NASA/TM-2018-219774, NASA, Moffett Field, CA.

Norman, D. A. (2013). *The Design of Everyday Things*. New York: Basic Books, revised edition.

Reitsma, J., Fucke, L., Borst, C., & van Paassen, M. (2017). Taking a Closer Look at Flight Crew Handling of Complex Failures – Ten Case Studies. In *19th International Symposium on Aviation Psychology (ISAP 2017)* Dayton.

Riegman, E. J. P. (2018). *Effects of Vertical Situation Diagram in 4D Trajectory Management Interface*. PhD thesis.

Rijndorp, T. A., Borst, C., de Visser, C. C., Stroosma, O., van Paassen, M. M., & Mulder, M. (2021). Aviate, Navigate: Functional Visualizations of Asymmetric Flight Envelope Limits. *Journal of Aerospace Information Systems*, 18(12), 933–948.

Tufte, E. R. (1990). *Envisioning Information*. Graphics Press.

Van Der Eijk, A., Borst, C., Veld, A. C., Van Paassen, M. M., & Mulder, M. (2012). Assisting Air Traffic Controllers in Planning and Monitoring Continuous-Descent Approaches. *Journal of Aircraft*, 49(5), 1376–1390.

Van Paassen, M. M., Borst, C., Ellerbroek, J., Mulder, M., & Flach, J. M. (2018). Ecological Interface Design for Vehicle Locomotion Control. *IEEE Transactions on Human-Machine Systems*, 48(5), 541–555.

6

Evaluation of an Operational Alerting Support

What is the impact on human performance if the pilot is provided with an operational decision-making support?

In Chapter 4, an Applied Cognitive Work Analysis (ACWA) was conducted which resulted in a set of Representation Design Requirements (RDRs). These requirements were translated into novel interfaces to support operational decision-making in Chapter 5. These five new displays were designed to lower workload and improve decision-making performance. However, the developed interfaces need to be evaluated to determine if the human performance objectives are met.

In this chapter, the results of a human-in-the-loop experiment are presented. This experimental evaluation will provide insight about the human performance implications with which the design objectives can be verified.

6.1. Introduction

Recent press releases confirm that industry and regulators are working jointly on operating concepts to reduce the required number of pilots on the flight deck (Frost, 2021). These concepts are part of the much-debated paradigm of Reduced-Crew Operations (RCO). RCO promises economic benefits, however, studies indicate that pilots require more troubleshooting time and make less well-informed decisions, when they are on their own on a modern commercial flight deck (Bailey et al., 2017; Faulhaber, 2019). These studies show unacceptably high levels of workload when operating under RCO. Interestingly, these workload issues are not unique to RCO; they also occur, although less frequently, during current two-pilot crew operations (Australian Transport Safety Bureau, 2013). Increased automation is often mentioned as the remedy to lower the pilot's workload, in particular automation that takes over the *'easier'* system management tasks (Bailey et al., 2017; Harris, 2007). However, it can be expected, based on observations from the past (Bainbridge, 1983), that introducing such automation might degrade situation awareness and decision-making performance even further, which is a worrying prospect.

With this in mind, an operational decision-making support was developed following a framework called Applied Cognitive Work Analysis (ACWA) to counteract the adverse effects of increased system management automation (see Chapter 4). ACWA was specifically developed by Elm & Potter (2003) to design effective decision-making supports. The prototype consists of five displays with multiple views, which are a combination of adapted current flight deck displays and newly designed displays to satisfy the requirements of the ACWA. The outcome of the ACWA, and therefore, the main idea behind this prototype is to show the impact on the flight plan resulting from ever-changing system capabilities and environmental conditions (e.g., a malfunctioning system or adverse weather conditions). It is hypothesized that this overview of impacts aids the pilot to make more informed decisions with less effort. The translation from the requirements to the visual form is a distinct process in which display design principles, such as visual momentum, become useful. This process was described in Chapter 5. However, the prototype is not yet been evaluated, so it is unknown if it is aiding the pilot in the decision-making process. This chapter presents the evaluation of the prototype.

The developed prototype gathers, analyzes, and transforms information automatically into flight-plan-relevant information, in a similar way humans process information.[1] The prototype is of an information automation type, since it will not create options nor make decision. Decisions are opted to be made by the pilot, such that s/he remain *'in the loop'*. The prototype is designed to support the pilot in its most important task as a decision-maker on-board of the aircraft.

In short, the working principle behind the prototype is that the overview is presented of operating constraints in relation to the goals of the operation. This overview enables the pilot to *directly perceive* the operational goals that still can be achieved. Moreover, the prototype alerts on an operational level, as a result the prototype will be referred to as the *'operational alerting'* prototype.

[1] This is a core principle of the Applied Cognitive Work Analysis (ACWA) as it structures information in a Functional Abstraction Network (FAN) which is inspired on how humans process information.

The aim of this chapter is to evaluate this operational alerting prototype with an extensive human-in-the-loop experiment to determine the influences of this prototype on **decision-making**, and **workload**. The prototype will be compared with a modern flight-deck set up to determine these influences. Another part of the experiment is to evaluate the **usability** of the novel displays; a crucial factor for the performance of interfaces and user-centered design. The results of this experiment will verify if this prototype is working as intended and if the ACWA is effective as a design-method for decision-making supports.

Based on the discussed design premises, the following three hypotheses will be tested in this experiment:

H_1 The use of the prototype displays will result in more well-informed decisions as can be expected from the ACWA method.

H_2 The experienced workload of the pilots will be less than the baseline flight deck supports while using the prototype, since the pilots only but have to decide, and are not occupied with gathering all relevant data.

H_3 The pilots using the prototype displays will require less time to manage the abnormal event since information does not have to be acquired manually from operating manuals and tables compared to the current flight deck support systems. This can be expected due to the elevated LOA at the information acquisition and analysis stages.

In the next section, the prototype is further elaborated upon. Then, the experimental setup will be presented, which is followed by results of the experiment.

6.2. Operational Alerting Prototype

The operational alerting prototype is implemented on three main displays on which five display elements are presented, which are the Horizontal Situation Display (HSD), Vertical Situation Display (VSD), Time and Velocity Situation Display (TVSD), Alerting and Task Display (ATD) and the Functional System Status Display (FSSD) (see Figure 6.1).

Flight-plan management is supported by showing the operating space and impacts on the flight plan. A flight plan or a path is expressed in four dimensions horizontal, vertical, and time, which is a result of speed. Limitations (or constraints) on the flight plan can be encountered across all these dimensions and need, therefore, to be reflected in the displays. For example, restricted airspaces limit horizontal and vertical operation, where the performance of the plane is limiting the speed profile.

Since the prototype is focused on flight plan management it shows the operating space (i.e., resulting from the capabilities of the aircraft), the flight plan, and the associated constraints within these dimensions. This is the reason to express the flight-plan with three dedicated display elements, each presenting one aspect of operation. The horizontal operating space and paths with their corresponding constraints are presented on the HSD (see the upper display element the display marked with the 1 in Figure 6.1). The operation is presented from a vertical perspective on the VSD (see the lower display element on the display marked with the 1 in Figure 6.1). This displays shows a projection along the flight path. This same projection is present by the TVSD, which shows the operating space and its constraints from a time-velocity perspective, as marked with the number 2 in Figure 6.1. The HSD also presents the status of the 'ground' and passenger domain, as it presents available runways, and feasible airports. These impacts are the result of the transformation of system capabilities, and environmental conditions.

The system capability is presented as an overview on the FSSD (see the display element on the right-hand size marked with the number 3 in Figure 6.1). This overview presents if a functionality is lost, if the function has only a single redundancy, or if the function will be lost under a certain condition (e.g., for systems that can fail if operated at a higher altitude). The functions are categorized in groups. The upper part of the FSSD is reserved for the implications that the system status is imposing on the operation. However, a non-normal system state does not necessarily cause an operational alert. Take for example an inoperative yaw damper, which degrades flight stability, however, this is only a 'serious' problem when turbulence is encountered. If no turbulence areas are crossed, no to little will be noticed from this failure. Nevertheless, the FSSD shows these implications to support the pilot's awareness.

6

System malfunctions can have a large impact on the operation. In such scenarios the priority of the pilot is to reconfigure the system to stabilize the systems and restore functionality, first. This task is supported with checklists which are presented by the ATD (see the display element on the left-hand side marked with the number 3 in Figure 6.1). The checklists otherwise presented in the Electronic Checklist (ECL) are presented in the ATD. Due to limited space, checklists were shortened, and irrelevant or overridden items are suppressed. Each next step will appear once the previous step is completed. Each checklist appears as a button with the checklist title, which can be accessed by pressing it. The prototype does not have an Engine Indicating and Crew Alerting System (EICAS) display, since this is replaced by functional information on the FSSD and, if procedure exist, by the ATD.

Besides the checklists, the ATD presents also operational impacts on the flight plan as *'operational alerts'*. The operational alerts present the *'broken'* parts of the flight plan, which require awareness, or require *'fixing'* through replanning. The operational alerts presented on the ATD as list items, can be clicked to access more information or possible solutions. However, these list items correspond with what is presented on the other displays.

All the concept display elements work together, utilizing the visual momentum principle (Woods, 1984), to provide an overview across all dimensions. It supports the pilot to comprehend where, when, and how the flight plan will be affected. The concept is dynamic; it checks in real-time the state of the plane, its environment, and compares it to the intended operation to determine if and where the current flight plan requires 'fixing'. However, options or recommendations are deliberately not provided, since the pilot should perform the 'fixing' process manually to keep the pilot cognitively engaged during the process.

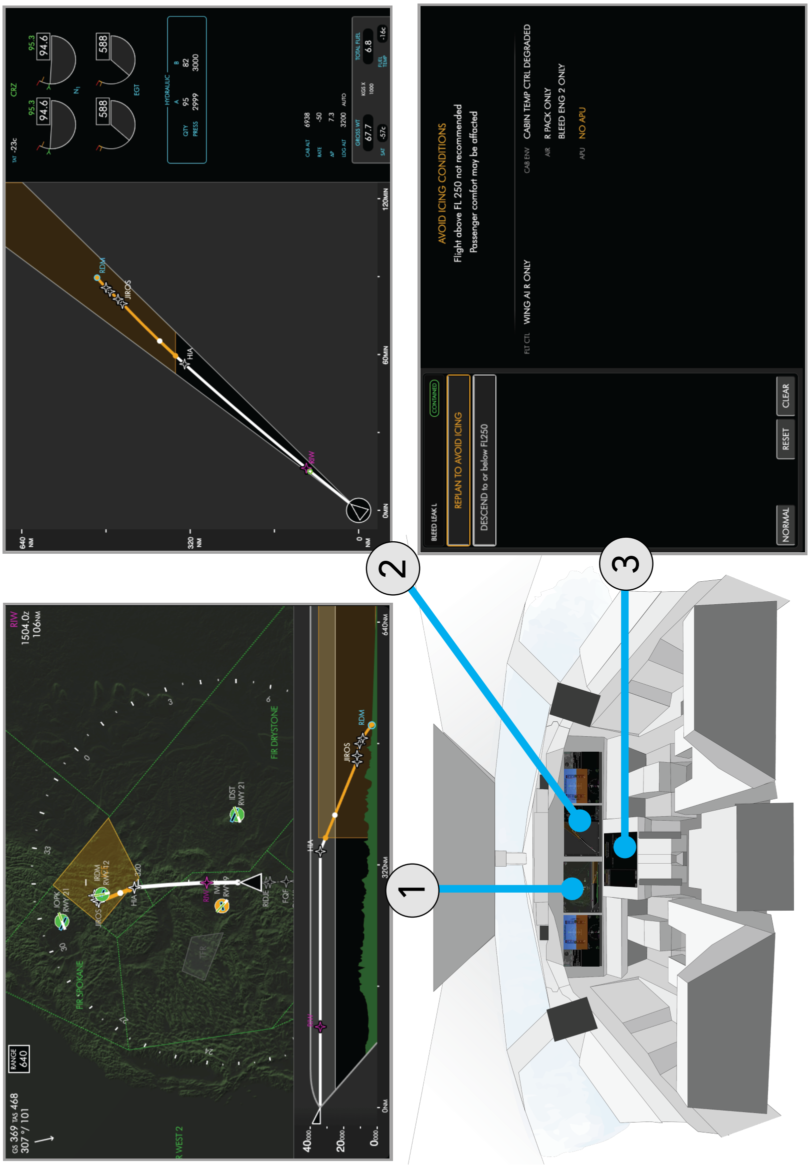


Figure 6.1: The operational alerting concept. With (1), the Horizontal Situation Display (HSD) and below the Vertical Situation Display (VSD), (2) Time and Velocity Situation Display (TVSD) on the left side of the display (3) Alerting and Task Display (ATD) on the left part of the display and the Functional System Status Display (FSSD) on the right side of the display.

6.3. Method

6.3.1. Participant Characteristics

In total, thirty-two (Dutch) airline pilots participated in the experiment. The group consisted of twenty-two captains and ten first officers. All possessed, or had possessed, an Airline Transport Pilot License and Boeing 737 type-rating. Many of the pilots also had previous experience on other aircraft types (from regional to wide body), and they had a variety of (previous) employers. The average age of the pilots was 43.2 years (SD = 8.9)[2], and had been flying commercially on average for 18.8 years (SD = 8.9). The total flight hours average was 9324 (SD = 4239). The average hours on the Boeing 737 series was 4243 (SD = 2868), see Figure 6.3 for more details. In short, all of them were familiar with the systems, procedures, and controls of the Boeing 737. Of the thirty-two pilots, thirty pilots were male, and two were female. Hence, the sample group is a representable reflection of real-world pilot population[3].

The pilots enrolled voluntarily, were entitled to a travel cost compensation from their home address in the Netherlands to the Simona Research Simulator (SRS) at the Delft University of Technology and consented to the privacy and safety statements before they participated in the experiment.

6.3.2. Independent Variables

6

The experiment was conducted over two dimensions of independent variables, (1) the flight deck configuration, and (2) scenarios. The design is, however, mixed to enable responses on usability from the entire participant pool.

Flight-deck Configuration

The flight deck configuration is a within-participant independent variable. The effect of the novel interfaces on human performance can only be quantified if it is compared with a reference flight deck. The Boeing 737-800 architecture is taken as a point of departure, for practical reasons such as the availability of technical documentation, simulation models, and pilots. However, the Boeing 737-800 cannot be considered a state-of-the-art flight deck, because it is lacks common flight-deck supports like Engine Indicating and Crew Alerting System (EICAS) and Electronic Checklist (ECL). These technologies have proven to decrease cognitive workload and reduce human error (Boorman, 2001). Comparing the prototype with the flight-deck of a Boeing 737-800 is, therefore, a step backward. Instead, the Boeing 737-800 flight deck was slightly modified to represent a modern flight deck with large touch-enabled displays, EICAS, and ECL (see Figure 6.2a), further referred to as the baseline configuration or Boeing 737 'modernized'. However, the systems and physical switches were kept like the Boeing 737-800. The Boeing 737 Max also has large screens and is very similar to our adapted version, except for the EICAS, and ECL. A slight difference between a real ECL and the ECL used in our set-up is that the conditional statements —items where the user has to select the appropriate condition— are not automatically sensed and completed. In our set-up this needed to be done manually, leaving some room for errors.

[2]The average European airline pilot is 43.7 years (in 2016) according to CAE (2017)

[3]4.22% of the airline pilots in the US are female, based on FAA data, according to (Pilot Institute, 2020)

The setup with the novel interfaces (concept configuration) is a variation to this Boeing 737 'modernized', where the ND, EICAS, and the forward pedestal displays (presenting the ECL) were replaced with the operational alerting prototype displays. The other systems, controls, and interfaces were kept similar to the Boeing 737 'modernized' (see Figure 6.2b).

The consequence of this is that pilots are new to both flight deck interfaces. However, the differences of the baseline were small compared to the difference with the prototype. The flight deck effects (illuminated lights) presented during a certain failure were all checked with a certified Boeing 737-800 training device. The presented EICAS messages in the baseline and prototype were translated and conforms to the Boeing 787 phraseology.

(a) Baseline configuration, Boeing 737 'modernized'

(b) Concept configuration, Boeing 737 'modernized' with operational alerting concept

Figure 6.2: Flight-Deck Configurations

Scenarios

Each system-failure scenario has its own unique set of tasks, inoperative systems, environmental conditions, and consequences, which result for each case into a different decision. Failure scenarios cannot be presented twice since the decision would then be made quicker due to the previous experiences. Therefore, the scenario is a between independent variable. The combination of failure and environmental conditions were all treated separately in this experiment. Four scenarios with each a different combination of failure and environmental condition were completed by each participant. The scenarios were designed to provoke and test decision-making. Three of the scenarios were designed to have different environmental conditions by introducing icing and turbulence areas. The combination of failures and these environmental conditions made each scenario unique. However, many aspects are kept constant, to avoid confusion. The experimental runs were initiated from the same point —2 hours and 15 minutes after take-off— at an altitude of 34,000 ft, and the remaining time to the destination was 2 hours. The scenarios were as follows:

The first scenario, a **fire in the forward cargo compartment**, is based on an incident described by the Transportation Safety Board of Canada (2018)[4]. During this scenario the following happened; 35 seconds into the simulation, the fire bell sounded, the *CARGO FWD FIRE* light illuminated, and the associated EICAS message appeared. Consequently, the corresponding checklist appeared on the ECL, and ATD, for the baseline and concept, respectively. The checklist prescribes to discharge a bottle of halon, a fire suppression gas, in the cargo compartment, and plan to land at the nearest suitable airport. The fire suppression system is certified to sustain a minimum concentration of 3 percent Halon for 60 minutes to prevent re-ignition on the Boeing 737-800. If the Halon escapes the cargo compartment, oxygen can enter and can cause the fire to (re)ignite.

The second scenario was simulated as a **leak in the left bleed duct** inspired on an incident reported by the AAIB (2010). Prior to this leak, the following CPDLC message was presented: *'GRANDWALL FIR SEV ICE OBS N OF N46 SFC/FL300 STNR NC'*. This message announced that in a part of the Grandwall Flight Information Region (FIR) severe icing conditions had been observed (see the area indicted by the number 1 in Figure 6.4, the airspace overhead the destination airport). This message appeared 10 seconds after the beginning of the simulation. At t = 45 seconds, the left *WING BODY OVERHEAT* light illuminated. A wing-body overheat condition is caused by a bleed air duct leak. It is sensed by the overheat sensors across the plane. Concurrently, the associated EICAS message and checklist were presented. The checklist prescribed to isolate the right bleed air supply, and switch off the left bleed air supply, resulting in a single pack operation as the aircraft was dispatched with an inoperative APU. The packs are responsible to pressurize and to supply temperature-controlled air to the cabin. A single pack can maintain pressurization but will be stressed by doing so. However, once airborne no limitations are imposed by the Miminum Equipment List (MEL) on single pack operation. However, if the event had happened before take off, then the MEL states that the flight altitude should remain at or below FL250. In any case, if the pressurization cannot be maintained, the plane has to descend to 10,000ft, which is not always possible overhead mountainous terrain. The left bleed system also supplies, inter alia, hot air to the left-wing anti-icing system, and since the bleed systems were isolated, the left wing anti-ice system became inoperative. The right-wing anti-icing system was still supplied with hot air, however, to avoid asymmetric ice built-up the entire wing anti-icing system needs to be turned off according to the procedures.

The third scenario was a scenario in which **a combined loss of an hydraulic and anti-skid system** occurred. This scenario was inspired on an incident reported by the Icelandic Transportation Safety Board RNSA (2018). Two seconds after the beginning of the simulation two messages appeared, stating: *'DRYSTONE FIR SEV TURB OBS W OF W101 FL120/FL410 STNR NC'*, and *'DRYSTONE FIR SEV TURB OBS S OF N44 AND W OF W100 FL150/FL380 STNR NC'* —both described turbulence areas located east of the current position (see the spaces indicted by the number 2 and 3 in Figure 6.4). According to the original flight path, one of the two spaces will be crossed within half an hour. This forms no immediate threat if all passengers and cabin crew are seated under normal conditions. However, at t = 110 seconds, a hydraulic leak appeared in system B, as a delayed result from a tire burst. As a result two *LOW PRESSURE* lights illuminated on the over-

[4]The failure is replicated. However, each of the incident-inspired scenarios differ in the moment the failure was introduced and environmental conditions.

head panel, indicating that both the *ENG 2* hydraulic pump and *ELEC 1* hydraulic pump sensed a low pressure condition. At the same time the EICAS messages; *HYD PRESS SYS B, YAW DAMPER, ANTISKID INOP*, and the associated checklists appeared. This was accompanied by a low quantity flag on the synoptic panel. With an operative yaw damper, severe turbulence should be avoided as prescribed by the checklists. The checklist also prescribes to power the rudder by the standby hydraulic system. As a result, Autopilot B became inoperative, but in the scenario Autopilot A was connected. Another consequence of these failures is an increased landing distance caused by two factors. The first is the loss of hydraulic pressure B, in response to which the checklist prescribes a landing configuration with manual braking, and flaps 15 —to guarantee sufficient go-around performance. The required landing distances for many normal and non-normal cases are described in performance tables. The second factors is the antiskid failure, which increases the landing distance even more. However, performance data was only available for flaps 40, not flaps 15 which was needed as prescribed by the loss of hydraulic B system checklist. The required landing distance needed, therefore, to be estimated. Furthermore, in this scenario the landing gear cannot be retracted once lowered. An extended gear increases drag drastically, the choice for an airport was, therefore, in this scenario one of full commitment without escape alternatives.

In the fourth scenario, a failure of the **left generator drive and the AC bus 1** was introduced. This unlikely event caused many inoperative systems at the same time. This was explicitly chosen to overload the pilot. In this scenario, all the messages about icing conditions, and turbulence conditions were presented within the first six seconds. After 82 seconds in the simulation, the generator drive on left side failed, indicated by the EICAS message *ELEC GEN DRIVE L* and the left *DRIVE* light on the overhead panel. Normally, this would not cause any consequential failures, but for this study's purpose the Bus Tie Breaker (BTB) failed to reconnect the bus. Hence, AC bus 1 remained unpowered and the messages *ELEC GEN OFF 1* and *ELEC AC BUS 1* appeared. Consequently, the systems that were powered by the AC bus 1 became inoperative which were indicated with the lights on the overhead panel and the following EICAS messages: *FUEL PUMP 1 FWD, FUEL PUMP 2 AFT, HYD PRESS ELEC 1, YAW DAMPER, HEAT TEMP PROBE, AUTOPILOT DISC, EQUIP COOLING EXHAUST, WINDOW HEAT L FWD, WINDOW HEAT R SIDE, ANTISKID, GND PROX SYS, HEAT PITOT ELEV L*, and *HEAT ALPHA VANE L*. All these messages have an associated checklist, which appeared on the ECL. Since the APU was still inoperative, a single AC source remained available in which case the checklist states to plan to land at the nearest suitable airport.

The participants required training to become familiar with the set-up and the experiment process. So, a training scenario was presenting in which both system malfunctions and environmental impacts occurred. The failures and combinations of failures are fictional and selected to familiarize the participants with completing checklists. In this scenario, after 5 seconds an ATC message appeared notifying that an airspace on their left was active. They would not cross it. After 13 seconds, the engaged autopilot disconnected and the EICAS messages appeared *AUTOPILOT DISC*. Twenty seconds later the EICAS messages *ENG FUEL FILTER BYPASS*, *ELEC TR UNIT 1*, and *FLIGHT DOOR UNLOCK* appeared. A consequence of blocked filters is that a flameout might occur soon. This forced them to land at the nearest suitable airport. Furthermore, the battery was discharging. This scenario was excluded from the data analysis but is presented here for completeness.

The previously introduced scenarios are summarized in Table 6.1. The order at which they were presented to participants is discussed later in Section 6.3.3.

Table 6.1: An overview of the scenarios presenting both the injected system malfunction and environmental conditions.

Scenario	System effects	Environmental condition
Training (T)	Autopilot A, engine fuel filters, TR unit 1, and flight deck door unlocked	Airspace R-4009 active (see Figure 6.4)
1	Fire in forward cargo compartment	none
2	Bleed leak in left wing	Icing conditions (Area 1 in Figure 6.4)
3	Loss of hydraulic system B, and antiskid	Turbulence conditions (Area 2,3 in Figure 6.4)
4	Left engine Integrated Drive Generator (IDG), and AC bus 1	Icing and turbulence conditions (Area 1,2,3 in Figure 6.4)

6

6.3.3. Experimental Conditions & Design

Experiment Design

Decision-making and Situation Awareness (SA) is largely based on experience (Endsley et al., 2003). This made a within-subjects (or repeated-measures) design for the scenarios impossible since the participant would recognize a failure scenario and would handle faster, influencing the measure for completing time for a certain display.

On the other hand, usability testing is another important part of the evaluation, which requires all participants to work at least once with the new displays. So, this experiment followed a between-subjects design for the combination of display and scenario with 16 data points. The scenarios are unique since they are a combination of system failures and environmental conditions.

Each flight-deck configuration presented messages, checklist, and impacts (for the novel displays) based on the failure condition. Therefore, each scenario and display configuration will give an *unique* test case. The participants presented with both the baseline and the concept display, to allow them to provide feedback on the usability post-experiment. The order in which the scenarios and display configurations were presented to the groups is presented in Table 6.2. The participants were presented with the baseline and concept interchangeably, starting with the baseline. The baseline was presented first to make the transition less steep. The test condition —combination of scenario and display type— was not seen twice by any participant.

The participants started with three training runs. After this, they were presented with the post-run survey, such that they knew what to expect during the proceeding runs. The data collected in the training sessions were not used in the analysis, and the participants were occasionally given some guidance on using the displays. Once the training sessions were completed, the real measurement runs started. Each run was followed by a post-run survey. After all runs, participants were presented with a final survey to review the overall process, which can be found in Appendix D.

Table 6.2: The experimental matrix, where B stands for Baseline and C for Concept displays. The scenarios are presented in Section 6.3.2 and summarized in Table 6.1.

	Experimental Run						
	Training 1	Training 2	Training 3	1	2	3	4
Group 1	Touch-panel training	ScTB	ScTC	Sc1B	Sc2C	Sc3B	Sc4C
Group 2	Touch-panel training	ScTB	ScTC	Sc2B	Sc1C	Sc4B	Sc3C

6.3.4. Control Variables

In this experiment there were three control variables, the participant group, operating environment and the available information sources.

Participant Groups

The participants were randomly divided into two groups (16 participants each). One group was performing the first scenario with the baseline while the others did it with the concept displays, this was alternated for all four scenarios. There was no significant difference in age, experience, nor other characteristic (see Figure 6.3).

6

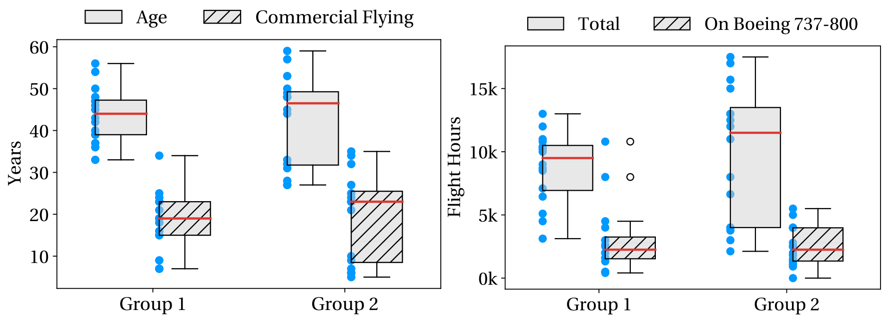


Figure 6.3: Participant characteristics between the two groups. No significant difference in any of the characteristics was found. Mann-Whitney rank test (U = 127.0, p = 0.492) for age, (U = 113.5, p = 0.298) for years of commercial flying experience, (U = 106.0, p = 0.208) for total flight hours, and (U = 122.5, p = 0.425) for flight hours on Boeing 737-800.

Operating Environment

As stated before, decision-making is a result of experience (short and long term). This implies that a pilot who flies a certain route frequently makes different, or faster decisions than a pilot who never flies that specific route. To mitigate this bias, a *'fake'* world is constructed with non-existing airport names, however, the used airports are renamed such that the airport are still based on reality and not everything is entirely fictional. The FIRs are, however, made-up and designed to challenge the decision-making process of the pilot. This gave every participant an equal knowledge base. As a consequence, it is likely to assume that pilots are slower in making a decision, since everything is unknown, have to be figured out, and double-checked. The pilot's decision was limited to go to either one of five airports in the *'fake'* world, which were IWLL, IRDM, IOPK, IDST, and IWLF (as shown in Figure 6.4).

Orville Wright Intercontinental Airport/**Warmhill (IWLL)** is the departure airport. This airport is George Bush Intercontinental Airport/Houston (KIAH) in the real world, which is a large airport with multiple very long runways at almost sea level.

Redmountain International Airport (IRDM) is the destination airport (Missoula Montana Airport (KMSO), in reality). This airport is located at 3206 ft above sea level, has terrain in the area, and has two runways. One runway is 2896 meters long, the other is 1406 meters long. IRDM has an ILS, two RNAV(GPS) and one RNAV(RNP) instrument approach. The shorter runway is closed, and the longer runway has a medium reported braking action. The airport is in the Grandwall FIR. Redmountain is advertised as winter seasonal holiday destination.

The destination alternate airport is **Oatpeaks International Airport (IOPK)**, which is in the real world Spokane International Airport (KGEG). It has two runways and a variety of instrument approaches. The available approaches at IOPK are: 2 ILS/LOC, 2 ILS with CAT II or CAT III, 5 RNAV(GPS), and 1 RNAV(RNP). This is introduced as the company's favorite airport in case of a diversion, since it is already been planned for. Its furthermore the company's regional hub.

6

The nearest airport is **Willowfort Regional Airport (IWLF)**. This airport is in real life Southwest Wyoming Regional Airport (KRKS), however, the Aircraft Rescue and Fire Fighting (ARFF) category is lowered to ICAO category 2 to challenge the decision-making process. At this airport, prior permission is required, if an air carrier wants to operate with more than 30 passengers. ARFF category 2 is sufficient for aircraft with an overall length of 9 m up to but not including 12 m. The Boeing 737-800 length is 40 meters and its minimal ARFF category, under emergency conditions, is 4 – under normal conditions it is higher. Hence, landing a Boeing 737 on this airport is not allowed since the fire-fighting services are not equipped adequately. IWLF has an ILS and a RNAV(GPS) approach for runway 27, where runway 9 has a RNAV(GPS) and VOR approach. The airport was advertised as a remotely located, old military airfield.

The airport located east is **Drystone International Airport (IDST)** and is inspired on Casper/Natrona County International Airport (KCPR), however, in the simulation this airport is moved a bit more eastward to make the decision a bit more challenging (N44°8′5.6862″*W*103°5′44.5308″). This airport was presented as a cargo airport with some facilities and a city nearby. It has two runways with a length of 3098 meters and 2645 meters. All runways have a RNAV(GPS) approach and runway 3 has also an ILS approach.

Flight Plan & Information Sources

The flight in the experiment was planned to go from IWLL to IRDM —a total time of 3 hours and 56 minutes (comparable with a flight from Amsterdam, The Netherlands to Antalya, Turkey; a typical flight for a Boeing 737-800). The aircraft had 181 passengers on-board and was dispatched with an inoperative APU. The pilots were briefed on the

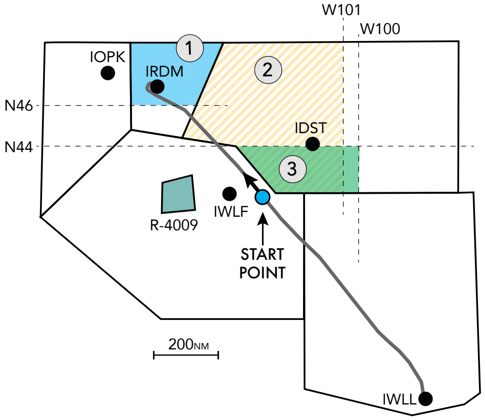


Figure 6.4: Map of the experiment flight plan with the possible airports, where (1) is the icing area presented in scenario 2 and 4, (2) and (3) are both turbulence areas that presented in scenario 3 and 4.

Table 6.3: Information provided during experiment

Call sign	DUT 961
Departure airport	IWLL
Destination airport	IRDM
Altn Destination	IOPK
Cruise altitude	FL340
Passengers on board	181
Flight time	3:56 Hours
APU	Inoperative
Zero fuel weight [kg]	60,900
T/off weight actual [kg]	75,300
Total fuel [kg]	14,695
Trip fuel [kg]	10,860
Altn fuel [kg]	1,895
Fuel at start [kg]	7,900

flight plan before the flight, and during the experimental runs they had the same information available to them in paper format. These papers included: the flight plan, the weather (METAR, TAF), the NOTAMs, a map, airport information with all the available approaches, and landing performance tables. This information can be found in Table 6.3 and in Appendix C.

6.3.5. Dependent Variables

The impact of the prototype on decision-making performance and workload cannot directly be measured since both measures are constructs. However, they are indirectly reflected through a variety of measures (both quantitative and qualitative, subjective, and objective). The user experience of displays was measured by questioning the pilots about their experiences and opinions, and by measuring the number of errors they made while executing a task. First, the variables used to measure decision-making are elaborated.

Informed Decision-making

The prototype has the purpose to improve the decision-making performance of the pilots. Decision-making is, therefore, the key variable in this experiment. Decision-making depends on personal experiences and on how risk-averse a person is. This means that there is no such thing as an objectively *'right'* decision since the decision dependents on previous experiences and the beliefs of the individual. Regardless of the outcome of the decision, a decision should be based on accurate information; the decision should be well informed.

During each test run, pilots needed to specify the plan of action for the remainder of the flight, after the introduced non-normal events. Participants needed to decide about; the landing destination, the landing configuration, the runway, and how the flight path should be altered based on their expertise and observations. From all these factors, the landing distance required can be calculated. The pilots were also asked to calculate or estimate it by themselves. Decisions on the **final destination**, the **error between the estimated and real landing distance required**, and the capability to perform **instrument approaches** are variables that encapsulates their comprehension of the situation (i.e., what environmental and system state variables did they take into account, and which not). But they do not tell the whole story.

A decision in which a participant choses a *'safe'* airport does not necessarily count as an informed decision, since a pilot can choose the right airport by coincidence. Instead, the participant was required to mention all consequences considered in the choice of their preferred destination airport. It is important that all repercussions are understood before the decision is made, to avoid surprises at a later stage of the flight, when no other options are available. Informed decisions are measured in this experiment by determining the awareness of **scenario-relevant factors** (marked in bold), or decision-driving factors. A decision will be counted as informed, if all the following factors are mentioned by the pilot, or a proof of understanding is provided in the post-run survey.

In the cargo compartment fire scenario, the pilots were instructed by the checklist to: **Plan to land at the nearest suitable airport**. IWLF is the nearest airport, but the pilots needed to determine if this airport was suitable. To answer this, the pilots needed to be aware of the **ARFF ICAO cat 2 at IWLF**. This is relevant —if assumed that the cargo fire is extinguished— since the cargo fire can re-ignite when the fire suppression gasses are dissolved. If they fully understood that no support is available on the ground at Willowfort (IWLF), but accepted it, and chose this airport as their landing site, then it was scored as an informed decision. If the pilots would fly to Drystone (IDST) —the next nearest airport— without noticing the ARFF category, but merely divert to IDST because IWLF requires prior permission, or a 30 minutes notice period; then this was marked as uninformed.[5] If the pilots opted to fly to the destination (IRDM), destination alternate (IOPK), or the departure airport (IWLL) —all longer than 60 minutes flight time— and if they did not mention they had protection for 60 minutes, then they would be scored as not sufficiently informed.

In the bleed leak scenario, the planned path is crossing a **severe icing area at the Grandwall FIR**, which is the FIR where the destination airport was located. They should have understood where this area was. If they mentioned that the destination alternate was not located within this icing area, then this was sufficient proof that they understood where the area was. This area was particularly relevant since the anti-ice systems were not operative in this scenario. The checklist prescribes to: "Avoid icing conditions". Hence, IOPK (if Grandwall FIR is avoided), IDST, IWLF (if the ARFF category is understood), and IWLL are informed options. However, this is not the only factor that should have been considered. The risk exists that the **remaining single pack might also fail and cannot maintain the cabin pressure** since it will be stressed, especially at higher altitudes (just like in the example incident). The stress on single pack can be reduced by flying at or below flight level 250 (as mentioned in the MEL, however in-flight this is not relevant). In case the remaining pack fails, an emergency descent to 10,000ft,

[5]The prior permission can be overruled at the captains digression, in an emergency, or with a mayday call.

or the lowest safe altitude (whichever is highest) needed to be conducted. If a descent was initiated, it required the consideration of two factors. The first of these is the **increased fuel consumption**, therefore, IWLL or IOPK cannot be reached (depending on where this loss of cabin pressure event happens). Also, on the way to IOPK, IRDM and IWLL, **high terrain** (10,000 ft or above) is encountered, which makes an emergency descent risky. They needed to be aware of high terrain and an increased fuel burn, if they proceeded to IOPK, IRDM, or IWLL, or opted to descent. The ones who chose to go to IRDM also needed to consider the **braking action of medium** at the only available runway.

The loss of hydraulic system B and anti-skid system had an obvious consequence on the landing distance. Especially, if the landing distance was already increased due to unfavorable conditions, such as a reported **braking-action of medium at IRDM**. Normally the runway-distance required can be calculated with a landing distance performance table, where each failure condition has its own entry, but in this scenario two failures became apparent. In the case of a combined failure, the flight crew should select the most conservative, that is, longest, landing distance (according to the instructions in the QRH). The hydraulic system failure dictates that flaps 15 must be used for landing, but the tables, that the pilots had available, showed the impact of the anti-skid with flaps 40 only. Even with flaps 40, the anti-skid failure is the most restrictive for the landing distance. So, the pilots had to point out that the condition they required was **anti-skid inoperative with flaps 15**. The runway at IRDM under those conditions will not be overrun (2712 meters required), however, the margin will be low (184 meters). This estimate is without any margin (for normal conditions this is 15%). Besides the impact on landing distance, the loss of the hydraulic failure caused an inoperative yaw damper, and as per checklist prescribes, areas of predicted moderate or severe turbulence needed to be avoided. **Severe turbulence areas in the Drystone FIR** (numbered with a 2 and 3 in Figure 6.4) are reported through CPDLC messages in the beginning of this run. They understood the locations of turbulence areas well if they noticed that the space overhead IDST had turbulence, and no other airport was affected. They also needed to mention that their current track was crossing the turbulence area (the area might be small, but they should be aware of it to avoid surprises). In short, IRDM is counted as well informed if the pilot considered the condition: anti-skid failure with flaps 15 and avoided or accepted the turbulence ahead. IRDM and IOPK could be reached if **the path was slightly adjusted to the left**, see Figure 6.4. Unlike IRDM, there was ample of margin at IOPK. If they chose IDST and planned to descend below FL120 or FL150, to avoid the turbulence, they needed to be aware of the **high terrain**. Accepting and crossing the turbulence is also counted as well-informed if they were aware of the exact location of the turbulence. Furthermore, the decision to go back to the departure airport (IWLL), or to go to the nearest airport (IWLF), was also counted as well informed, however, only if they correctly interpreted the turbulence and understood the **ARFF category (in the case of IWLF)**.

The electrical system failure scenario is a scenario in which many failures appeared; however the decision driving factors are as follows. The scenario starts with a message indicating the active **icing and turbulence areas** (the areas indicated with 1, 2, and 3); pilots needed to be aware of these. Also, the anti-skid system became un-powered.

This time, they were able to use the non-normal landing distance table entry for **no anti-skid, flaps 40**. Moreover, multiple anti-icing systems are unavailable (window heat, and probes), which forced them to avoid icing areas. Hence, if IRDM was chosen, they would have encountered icing conditions, causing reduced outside visual and erroneous instruments. Furthermore, the yaw damper was inoperative once more, so turbulence areas needed to be avoided as well. The checklist instructs to **plan to land at a nearest suitable airport** with a single AC source. IOPK and IWLL are far —more than two hours— and therefore are not considered near. This makes the decision hard since IWLF has still the insufficient **ARFF**, and IDST could have been reached without crossing turbulence by descending to FL150, but in this case they needed to be aware of the **terrain**. If the remaining AC source would also fail, they would have approximately 60 minutes on standby power (i.e., battery power).

In all the runs, the weather was similar, no instrument landing would have been required —minimum visibility was at lowest 7000 meters— and no restrictive clouds were present. The pilots were asked what approach they would fly and if, various **types of instrument landing** would be possible.

Workload

The second independent variable in this experiment was workload. The construct of mental workload is measured through several variables. The first variable is **experienced workload**, which is a subjective measure that can be obtained with the Rating Scale Mental Effort (RSME). The original Dutch version of the RSME is used since all pilots were native Dutch speakers.

Total run time is an objective measure that provides insights into the workload pilots experience during each run, where more time equates to a higher (task) workload. The end of the run was determined when pilots said: *"I'm done"*. They were instructed to say this out loud when they formulated their decision for the remainder of the flight. The pilots were instructed that this time was defined as the time at which they would start programming the new plan into the FMS, since the new plan needs to be formulated before one can program it. However, this measurement is a relatively rough measurement and depends on multiple processes, so some nuances need to be added.

Fault detection and diagnosis

The total run time consists of the *'steady state'* phase (time span until the moment the failure was introduced), the failure detection time, the checklist execution time, and the decision-making time. The **failure detection time** is defined as, the time from when the failure was introduced until the main failure was detected and explicitly pronounced. The **checklist completion time** is the time spent on resolving checklists, so the time when pilots were actively involved with completing the checklist. And finally, the **decision time** is defined as the time the pilot spent on formulating a decision, which is obtained by subtracting the failure injection time, detection time, and checklist competition duration from the total run duration. The decision time also includes time like scanning the cockpit or searching for and reviewing documentation. This breakdown of times allows to pinpoint possible issues with the interfaces at each of the steps of the process and compare each phase separately.

Usability

This experiment partly resembles a usability study, and thus the experiences of the pilots with the new displays or opinions about the clarity, or usability of the displays is important for the evaluation of the new support systems.

Another measure to determine how well the system management support performs, usability wise, is to measure the accuracy of the performed task. So, every error made in the switching, selecting a checklist input, skipped item, uncompleted checklist indicate possible issues with the interface, or task was marked.

6.3.6. Data Collection

Determining how informed a participant is, is not as straightforward as it seems, since one cannot look inside a pilot's mind. Thus, the level of awareness, for example, had to be determined through observations and surveys. The most important method of collecting data used in this experiment was, therefore, observations from video recordings (with audio), as the pilots were instructed to think aloud. The simulation software also registered button presses. The pilots were invited to speak out loud in Dutch or English, however, all spoke Dutch.

After each run, a survey was presented see Appendix D. These surveys asked the pilots to explain, by saying out loud: (1) what they observed on the flight deck, (2) what the underlying failures were based on their observations, and (3) all the factors they were considered for the remainder of the flight. Furthermore, the survey questioned the participant what approach, what airport, what runway, what landing configuration they were planning for, and what landing distance they expected. They were also asked in this post-run survey how they experienced the workload (to be answered with the RSME). This was followed with several Likert-scale questions (5 choices) to estimate the impact on flight safety of certain actions / maneuvers under the just experienced conditions (e.g., if it would be safe to execute an ILS cat III landing with the conditions they just observed). This provided additional evidence that they considered the scenario-specific factors. The experimental runs were followed by a final survey aimed to capture their opinion about the new concept.

6

6.3.7. Apparatus

The measurements were performed in the Simona Research Simulator (SRS) at the Delft University of Technology (see Figure 6.5), which was equipped with seven touch-displays with a similar layout as the Boeing 737 Max and Boeing 787. The SRS was further equipped with a physical Boeing 777 throttle-stand, a Boeing 737 Mode Control Panel (MCP), and a generic steering column. The pilots could manually steer the plane, in case they found fit, for example when the autopilots disconnected.

The displays were presented on four 15" 4:3 XGA touchscreens, the overhead panel was presented on a 42" 9:16 UHD touchscreen, and the aft pedestal panels were presented on a 19.5" 9:16 FHD touchscreen.

DUECA/DUSIME was used to process flight control, autopilot inputs and simulate the flight model for the Boeing 737-800 in Flightgear and JSBsim. This way the aircraft felt real in case of manual take-over. The failure scenarios were scripted and based on the effects of a Boeing 737-800 flight simulation training devices from Multi Pilot

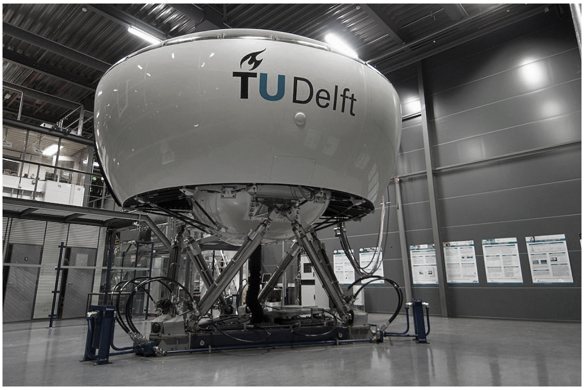


Figure 6.5: The Simona Research Simulator

Simulations BV (MPS). The displays were developed with web technology —HTML, Javascript, and CSS— which allowed to run all displays in a browser. All scenarios started at the same location, at FL340, with a speed of 282 kts, 0.81 Mach. The detailed initial conditions are presented in Appendix C.

6

System states were logged and in parallel audio and video were recorded, a back-up surveillance camera was used in case no video was recorded by the main camera. The surveys were presented after each simulation run on the forward pedestal touchscreen. At the same time, all other flight-deck control panels would be made black, such that all the observation needed to be memorized by the pilot.

For this experiment, the SRS was used as a fixed base simulator since motion at altitude is limited, and no approaches, nor landings were flown.

Training

The experiment started with a briefing introducing the aim of the project, the *'fake'* world with all its characteristics, the flight plan, and the task. After this, each participant received the same three training runs. The first training run was intended to familiarize the participant with the ECL and the touch controls, referred to as the touch-panel training in Table 6.2. During this training, the participants were asked to complete a fictional checklist, which made them locate some switches and learn how to operate buttons and selectors by touch. Once this touch-panel training was completed successfully, the participants were presented with the training scenario with the baseline displays. This training scenario was repeated with the concept displays. After this, a post-run survey was presented.

6.3.8. Data Diagnostics

Experiments are susceptible for errors and unforeseen conditions, especially if humans are involved. The presented indications on the displays needed to be comparable after all the system management tasks were performed to use the data in the analysis. Unfortunately, this was not always the case and various runs needed to exclude from the analysis. There were three reasons why certain runs were excluded, which are as followed:

First, some participants were unable to extinguish the fire due to faulty touch panel inputs. This would not have happened in on flight decks with physical buttons. Nevertheless, a scenario with an unextinguished fire is incomparable to a scenario in which the fire is extinguished. Hence, these runs were excluded.

Second, discrepancies also occurred due to software issues.

Lastly, incorrect checklist execution led to operational alerts and visualizations that would not appear. Checklists include items to select what condition is relevant. For example, 'Choose one: Both lights are illuminated, yes, or no?'. If a participant would select no, when the correct condition is yes, the automation will not present similar impacts. Hence, these runs could not be used in the analysis.

To conclude, the runs that differed too much from the intended scenario caused by one the three previously presented causes for discrepancies were excluded from the analysis. Three runs were excluded in scenario 1; four runs were excluded in scenario 2; two runs were excluded in both scenario 3 and scenario 4. This resulted in a minimum of 14 data points per display type per run.

6.4. Results

6.4.1. Informed Decision-making and Awareness

One of the aims of this experiment was to determine if pilots made more informed decisions when using the concept displays. Each pilot needed to decide what to do for the remainder of the flight based on the happened non-normal events. The most important decision the pilots had to make was whether a diversion was needed, and if so, to what airport.

Diverting Airport

The number of times each airport was chosen as the final landing site is shown per display-type group for each scenario in Figure 6.6. In the cargo fire scenario (scenario 1) and the electrical generator drive failure (scenario 4), the pilots were instructed by the checklist to 'plan to land at the nearest suitable airport', where the two nearest were IWLF and IDST. This obviously steered their decision; hence more variety is observed in the chosen airport during the second and third scenarios.

Figure 6.6 shows little difference between the baseline and the concept in the first two graphs. However, a small difference appears in the hydraulic leak scenario (scenario 3), where IRDM is more often the preferred choice of the pilots who used the concept displays. Another difference can be found in scenario 4, where IWLF was more often the preferred choice of the pilots who used the concept. This decision signifies part of their 'informedness'. Another indication about their awareness is the prediction of the required landing distance, which will be discussed in the next section.

Predicted Landing Distance

A measure that can signify how well the pilots were aware of the aircraft state and the airport' conditions is the estimated landing distance. Pilots were asked to predict the landing distance required —by using the performance tables found in the QRH— at

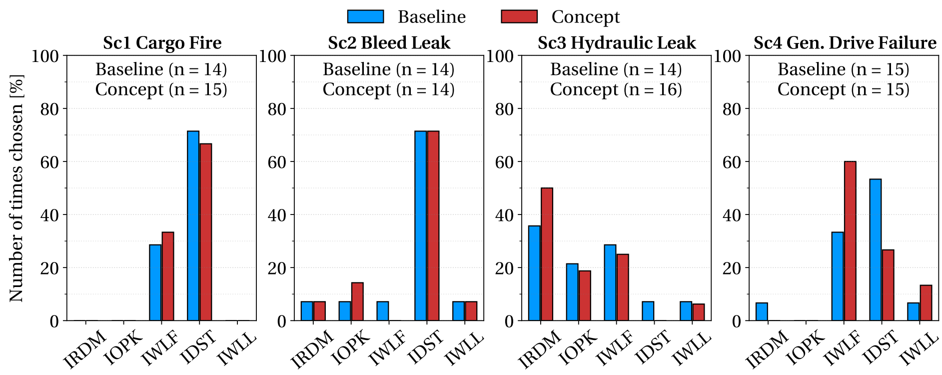


Figure 6.6: The final destination airport chosen by the participants for each scenario and display type. The unequal sample sizes are the result of errors in execution or failure to detect certain conditions (as described in Section 6.3.8).

the runway of their choice with their chosen configuration. They were instructed to perform this task as they would do operationally.

The following factors affected the landing distance in the presented scenarios: the braking action on the only active runway at IRDM was in all scenarios medium, and the anti-skid protection system was inoperative in scenario 3 and 4. Furthermore, only flaps 15 instead of 40 could be used in scenario 3. Hence, the third scenario was the most challenging due to the combined impact of the reduced flaps and anti-skid system.

The error between the estimated values and the actual distance at their chosen landing site is presented in Figure 6.7. Awareness of the variables, such as possible landing configurations, braking performance, wind, and runway conditions, are all captured in this prediction. Most of the predictions are within ±15% of the actual value in scenario 1, 2, and 4. Even though, the temperature corrections, elevation corrections, and slope corrections were often roughly estimated. In these cases, the pilots made a trade-off between accuracy and the time required.

However, the most notably difference in Figure 6.7 is observed in the third scenario; here many pilots predicted that they needed more landing distance than what was really required. The error was in some cases large, mainly because the tables did not provide a table entry with both flaps 15 and anti-skid inoperative and, therefore, pilots were not able to predict the distance accurately. This uncertainty made the pilots more conservative, estimating the distance on the safe side.

In the fourth scenario (electrical generator drive failure), nine of the 15 pilots who used the baseline displays did not understand that the anti-skid system was inoperative. They would have been surprised on landing to find their auto-brake system inoperative too. In comparison, only two of the 15 pilots who used the concept displays were also not aware of this impact.

Anyhow, all pilots chose a runway in combination with a landing configuration that ensured that no overruns occurred. This can be partly attributed to the long available runway distances at all the fields. However, most importantly for our study, no difference in the predicted distances as shown in Figure 6.7 was found between the baseline and concept groups. Next, the instrument approach decisions will be explored.

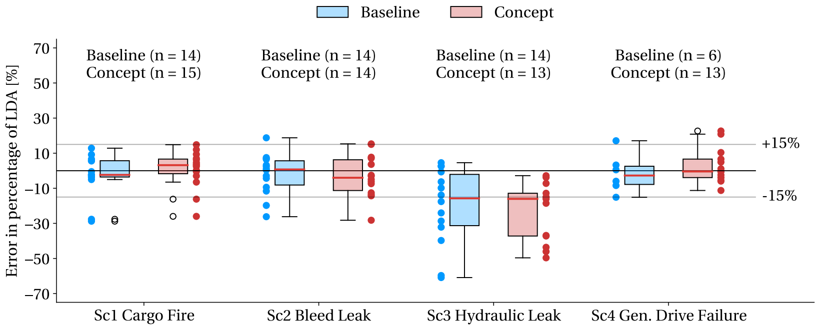


Figure 6.7: Error between the predicted landing distance and the actual landing distance as percentage of the landing distance available. Negative values indicate that pilots estimated they needed a longer landing distance than the actual distance, which is a conservative estimation.

Selected Instrument Approach

Malfunctioning equipment can impact the availability of instrument approaches. Take, for example, the third and fourth scenario, where only one autopilot was available. In this case, the autopilot Minimum Use Height (MUH) is restricted to 158 ft above ground level (Boeing, 2005). This implies that the instrument approaches with a decision altitude lower than the MUH cannot be flown automatically to the decision altitude but need to be aborted at the MUH, if the runway is not in sight. Consequently, all ILS CAT II & III approaches were affected in the experiment since the highest ILS CAT II decision altitude was 147 ft above ground level. Furthermore, the automatic flare capability was not available with single autopilot operation, which made ILS CAT III approaches even more risky.

Likewise, RNAV(RNP) approaches can only be conducted safely if a specific set of systems is operative, including the ground proximity system, and a radio altimeter. During the fourth scenario, both these systems became inoperative, and thus, RNAV(RNP) approaches were no longer feasible. Hence, conducting RNAV(RNP) approaches would be a high risk in terms of flight safety.

The weather conditions in the scenarios did not require high-precision instrument approaches; consequently, none of the pilot chose an RNP (RNP) or ILS CAT II or CAT III approach, since all chose either an ILS or RNP (GPS) approach. The post-run survey, however, questioned them about the risk involved, if they would opt for such high-precision approaches under the happened conditions.

Several participants in scenarios 3 and 4 did not consider the impact of the system failure on the instrument approaches. In the third scenario, four pilots using the baseline and five pilots using the concept displays indicated that ILS CAT III was still possible. In this same scenario, five pilots in both display-type groups indicated that ILS CAT II approaches were still feasible. Hence, we can conclude that there was no influence of the display indications in the third scenario.

6

However, all of the pilots who used the concept displays in the fourth scenario estimated that conducting an ILS CAT II and ILS CAT III would introduce a high risk. Of the pilots who used the baseline displays, five pilots indicated that both approaches were still possible. Hence, in this scenario the indications on the FSSD proved to be effective.

Regarding the RNAV(RNP) approaches, the pilots who used the new concept in the fourth scenario were slightly better informed. However, five participants stated that these approaches could be conducted safely, compared to 9 who used the baseline displays.

So far, the pilot's final decision was discussed (i.e., the chosen airport, landing configuration, runway, and instrument approach). This decision cannot be rated as good or bad, since it depends on personal experiences and preferences. What matters most is, if they were aware of the imposed risks, and if a risk was taken, if it was done deliberately. Hence, the rational behind the decision need to be studied (i.e., the awareness of scenario-relevant factors). The awareness of the scenario-relevant factors signifies the 'quality' of a decision. A participant who mentioned all relevant factors is considered 'fully informed'.

Scenario 1: Cargo Fire Scenario Relevant Factors

Pilots chose either IDST or IWLF in the first scenario, as can be observed from Figure 6.6. This was apparently influenced by a checklist item: *'Plan to land at the nearest suitable airport.'* The pilots had to determine which of the nearest airports —IWLF or IDST— was suitable. IDST was suitable, but not the nearest. However, IWLF was not suitable for a Boeing 737 due to the insufficient ARFF category.

6

Seven of the 14 pilots who used the baseline understood this limitation, even though two of those who understood that the ARFF category was too low, accepted the risk and chose IWLF as their destination. These two preferred to be on the ground and evacuate as soon as possible, which was backed-up by the comment, *"It's better to have a complete plane on the runway, than a half aircraft in the air."* On the other hand, two of the 14 pilots chose IWLF without being aware of the insufficient fire-fighting service.

The pilots who used the concept displays were somewhat better informed. The concept's display showed that IWLF was not suitable with an amber symbol for the airport, and by announcing that ARFF was too low. This indication was provided by a menu on the ATD, which was accessed by pressing the button stating: 'Plan to land at nearest suitable airport'. 11 of the 15 participants understood that the ARFF category was below the required category. Even though the display provided these indications, four participants remained unaware. Two of these did not open the relevant menu, in other words, they did not use the indications on the displays. One pilot relied too much on the display since he only used the color coding to decide not to go to IWLF. This indicates over-trust in the display indications, which can be dangerous if the display is presenting incorrect, irrelevant, or incomplete information. And lastly, one pilot incorrectly interpreted the menu. He assumed, based on his interpretation of the display, that IWLF was a good option with the appropriate ARFF category.

It is important to understand if the concept was the source of the awareness, or if pilots with the concept displays simply paid more attention to the briefing or documentation. In total, 13 pilots understood the insufficient ARFF category from the briefing (seven in the baseline group and six in the concept group). Five participants of the eleven who used the concept displays and understood the ARFF category obtained it from the concept indications. The others who understood the insufficient ARFF category – in both the baseline and concept – obtained it from the documentation.

Scenario 2: Bleed Leak Scenario Relevant Factors

Two factors played a role in the bleed leak scenario. The position of the icing conditions, and the possibility that the remaining pack could fail, and an emergency descent might be needed. This can become risky due to the high terrain, and increased fuel consumption for flight at low altitude (in case the participant opted to land at IOPK, IRDM, or IWLL). Next was the ARFF category at IWLF (if chosen), and lastly, the braking action, which was 'medium' at IRDM, relevant if they proceeded to this airport.

Only three of the 14 baseline group pilots interpreted the icing conditions correctly. The factor was marked as not understood, if they mentioned that icing conditions were also observed at IOPK. One of the three pilots who understood where the icing area was, decided to avoid the Grandwall FIR by going to IOPK. However, on the way to IOPK, IRDM, or IWLL high terrain would have been encountered (above 10,000 ft). This pilot was unaware of this terrain, and thus would have been surprised if the other pack had failed and an emergency descent was needed.

On the contrary, 12 of the 14 pilots who used the concept, correctly identified the icing area. This is quite a difference compared to the baseline. One participant that did not detect the ATC uplink and thus could not relate the amber colored area displayed on the display to the icing area. This participant tried to explain the indication by mentioning that the destination could not be reached because of increased fuel burn. The other participant who did not understand the icing area, did not use the prototype display, and instead asked for a significant weather chart (i.e., the tool used by pilots in day-to-day operation).

Despite being aware of the icing areas, one of these 12 took the risk to go to IRDM based on previous experience with icing conditions. His experience was that in real life these messages are somewhat exaggerated and conditions are rarely as bad as presented. However, he did not mention the reported braking action medium. This would not have had a serious impact since the landing distance required was still well within limits.

Three of the four participants, who interpreted the icing conditions correctly with the concept displays and chose to go to either IOPK, IWLL, or IRDM, were not fully aware of the high terrain. Most of the pilots who used the concept displays diverted to Drystone due to this insight instead.

It is interesting to note that three participants with the baseline mentioned the MEL recommendation to limit the altitude to FL250 with a single pack. Two pilots initiated a descent and one maintained FL340, while frequently checking the cabin pressure. With the concept display, 12 participants mentioned the recommendation, 10 planned to descend and two maintained FL340. This recommendation was presented on the display, which explains the difference.

Scenario 3: Loss of Hydraulic System B and Anti-skid Relevant Factors

Participants in general scored the lowest on informed decision making in the third scenario. In this scenario, multiple factors played a role which were, turbulence areas which should have been avoided due to an inoperative yaw damper, braking action 'medium' at IRDM combined with the increased landing distance resulting from *two failures* (i.e., loss of hydraulic system B and anti-skid). All these factors needed to be mentioned by the subjects to pass as well informed.

In this scenario, severe turbulence was reported in parts of the Drystone FIR, which needed to be avoided as prescribed by the inoperative yaw damper checklist. All the participants that used the concept displays correctly interpreted the turbulence areas. They were aware that they were crossing these if they would continue the planned path. For the baseline group, five of the 14 pilots understood this correctly. The nine that did not interpret the turbulence areas correctly thought that turbulence was observed everywhere west of 101 degrees west, and that therefore they were currently in turbulence conditions.

The 14 of the 16 pilots with the concept displays avoided the area by turning left, climbing, or turning back. The other two pilots accepted to cross the relativity small turbulence area, however, they were aware of this. Regarding the 14 pilots with the baseline displays, five crossed the turbulence area and nine did not. Of the pilots who did not cross the turbulence area, four deliberately choose to change the route to avoid the area ahead, and the other five either went to IWLF or IWLL. Of the five pilots who crossed the area, one pilot was aware, but four pilots who crossed the turbulence were not aware of it. Moreover, one pilot decided to go to IDST, and therefore crossing two severe turbulence areas without being aware of it.

The other important factor was the awareness that the loss of the hydraulic system B and anti-skid were two separate failures, each contributing to an increased landing distance. Seven of the 30 participants were aware of this, and therefore, it is the least detected effect of the experiment. It is an important factor while determining the landing distance. Three pilots with the baseline, and four pilots with the concept identified the failures as separate conditions correctly. Interestingly, the seven pilots that used the concept, fully trusted the concept display indications, and did not calculate nor check the landing performance distances presented by the concept. Some who checked the calculations did not trust the outcome. Consequently, they calculated the values themselves, and since this was impossible to do accurately —because of the lack of information in the table— they became skeptical and made very conservative estimates of the landing distance required.

Another important factor while calculating the landing distance is the awareness of the reported braking action of 'Medium' at IRDM, which significantly increases the landing distance required. Only six pilots of the baseline group, and two pilots of the concept group correctly understood this.

Furthermore, if the pilots were planning to land at IWLF they should be aware of the insufficient fire-fighting category. In total eight participants opted for IWLF, four pilots used the concept displays and four used the baseline displays. For both the concept-display and the baseline-display group, one out of these four was aware of this limitation; and the other three not. The decision becomes significantly easier if this airport condition is not considered.

Scenario 4: Generator Drive Failure Relevant Factors

In the last experiment run, the pilots were instructed by the 'Generator drive' checklist to land at the nearest suitable airport. They further needed to understand the location of the turbulence and icing areas, plus that these areas should be avoided due to unpowered systems, such as the yaw damper, window heat, and various icing probes. This awareness of the inoperative systems is important, since normally these areas can, if needed, be crossed. This scenario is comparable with the first scenario, however, now a turbulence area made Drystone less favorable.

The turbulence area was correctly interpreted by three of the 15 the baseline-display pilots (i.e., understanding that the turbulence is ahead and right of them). This was much lower compared to concept-display group, where all the 15 pilots understood the location of the turbulence areas. Three of the 12 pilots who used the baseline displays and incorrectly interpreted the turbulence areas crossed the turbulence unintentionally.

And finally, the anti-skid failure was detected seven times by the baseline group in scenario 4. Eight pilots selected an auto-brake setting other than manual, which would not have functioned. This is higher compared to the group who used the concept displays, where only two pilots did not select the manual autobrake.

Informed Decision-making

So far, data on the final decisions and the awareness of the scenario relevant factors is presented. Based on this, the number of informed runs can be determined. Runs in which the pilot was aware of *all* the scenario-relevant factors were marked as an informed-decision run.

The total informed runs for each scenario and display configuration is presented in Table 6.4. The pilots who used the concept displays made more informed decisions, compared to the pilots that used the baseline set-up. Almost three times as many informed decisions. It is apparent from Table 6.4 that the pilots who used the baseline in scenario 2, 3, and 4 scored low on informed decision-making. Also, the pilots who used the concept in scenario 3 scored low on *"informedness."*

Hence, it can be stated that the concept display resulted in more informed decisions.

Table 6.4: Comparison between baseline displays and concept displays for informed decisions per run.

		Scenarios				
		Sc1	Sc2	Sc3	Sc4	
	Runs	**Cargo Fire**	**Bleed Leak**	**Hyd. Sys loss**	**Gen Drive**	**Total**
Baseline	Informed	7 (50%)	2 (14%)	1 (7%)	2 (13%)	12 (21%)
	Total	14	14	14	15	57
Concept	Informed	11 (73%)	8 (57%)	3 (19%)	7 (47%)	29 (48%)
	Total	15	14	16	15	60

6.4.2. Workload

Experienced workload

The workload the pilots experienced within each scenarios was measured with the RSME, which was filled out after each simulation run, and the results are presented in Figure 6.8. A non-parametric test was used since the sample size was at maximum 16. The first three scenarios show no significant difference in the experienced workload, but pilots that worked with the concept during the electrical failure scenario (scenario 4) were experiencing a significant higher workload, according to the Mann-Whitney U test (U=63.5, p=0.022).

This result differs from what was hypothesized in H_2. This may be caused by the number of completed checklists, which was lower for the participants with the baseline (M = 7 versus M = 12.4 for the participants with the concept). Hence, more tasks could result in a high RSME score.

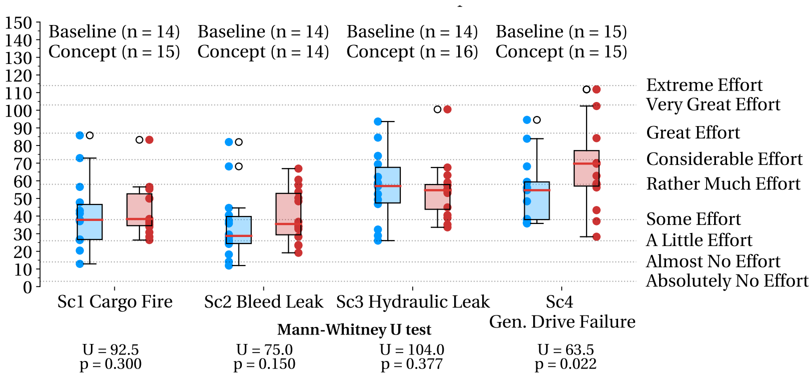


Figure 6.8: Experienced Workload during each scenario with the RSME scale, comparing the baseline with the concept group.

Time to completion

The total run time to completion is a global objective performance measure that reflects the performance of all elements of the display. Issues with detection and checklist execution will result into higher values. The total-run time can, therefore, be used to quantify the overall performance. The results are presented in Figure 6.9. The data shows one significant difference, again in scenario 4, according to the Mann-Whitney U test (U=55.0, p=0.009). This non-parametric test was used due to the same reasons as mentioned previously. In this case, pilots who used the concept displays needed more time to finalize their decision, approximately 6 minutes more. In the other scenarios no significance is found. However, the data hints towards a timesaving of approximately 1 minute, and 3 minutes for the concept-displays in the first scenario, and third scenario, respectively. The contrary happened in the second scenario, where the concept-display group is about 2 minutes slower in completing the scenario. The reasons behind these differences could be found in the following.

In the third scenario, the landing distance needed to be calculated because of announced the hydraulic failure and anti-skid problems. The concept presented the calculated landing distance with a bar, representing the runway with the landing distance required, which is updated according to the context. Therefore, many of the pilots that used the concept display did not manually calculate the landing distance, which saved time.

However, a few participants did not trust the automation for the complex case of two independent system failures (hydraulic system failure and the anti-skid) that resulted in an increased runway length. These few participants that calculated the landing distance manually took more time. If the participants who manually calculated this are excluded from the sample, a significant difference is found (U=56.0, p=0.047) and the pilots with the concept displays were in this case 5 minutes faster on average (32.5%).

In the fourth scenario, a total 16 of checklists appeared and could be completed. However, only 4 of the 15 pilots who worked with the baseline completed all 16 checklists. Others stated that the systems were consequential failures and focused on re-planning. They furthermore said that most of the systems will remain un-powered and could not be brought back. The average number of completed checklists with the baseline was 7 and with the concept 12.4. Hence, the Alerting and Task Display (ATD) of the concept made more pilot complete more checklists.

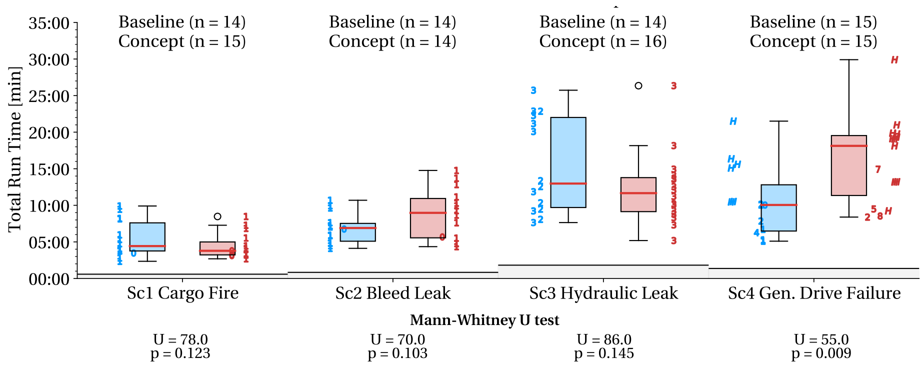


Figure 6.9: Total run time is largely influenced by the number of completed checklists (i.e., more time spend on the checklist results in a long run time). Therefore, the number of completed checklists are plotted with the number and with an offset on the x-axis, fewer completed checklists are plotted closer to the box plot. The H-marking indicates that 10 or more checklists were completed. The rest are marked with the number of completed checklists.

Detection time

The detection time is an important factor for a failure scenario. If the failure is not detected promptly, the response will be delayed, so will the total troubleshooting time. The time between the failure injection and calling the main issue out loud was defined as the detection time. The main issues were a fire in the forward cargo compartment, a bleed leak on the left side, the loss of hydraulic system B, and a generator drive failure, for scenario 1, 2, 3, and 4, respectively. The results are presented in Figure 6.10. No significance was found, but scenario four is very close to significance (U=73.5.0, p=0.055).

A delayed detection shows an issue with the interface design, more specifically the perception part. Although on the Boeing 777 and 787 a caution alert is accompanied by an aural alert, which was not the case in this simulation, because it followed the Boeing 737 flight-deck effects (on the Boeing 737 the master caution has no dedicated aural alert). The bleed leak was announced on the concept display with a single, relatively small, box on the left corner of a display not in the forward field of view, but on the forward pedestal. The alert was presented with a low visual salience. The viewing angle of the used displays also made it more difficult to detect. As a result, six of the 14 participants detected the problem late. This increased the average total run time for scenario 2.

In the third scenario, the anti-skid checklist was presented first on the baseline displays. Once a checklist is initiated on the ECL, the display will not return to the menu where all checklists are presented. Although all failures were presented by the EICAS display, most pilots were only aware of the hydraulic failure after completing the anti-skid checklist.

In the fourth scenario, the baseline, more specifically the ECL, presented the underlying issue first, which was the *ELEC GEN DRIVE 1* checklist and therefore it was easy for the pilots to detect. In the concept-display group, pilots had to scan the list with various checklists to determine what the underlying failure is, making detection slower. This led to a result that was very close to significance (U=73.5.0, p=0.055). The large variation of detection time was probably caused by pilots who did not detect the failure at first, but once they went though some checklists they figured out what the cause was. Also, more effects appeared, such as amber spaces, and a whole series of functional status messages. This made detection slower compared to the baseline ECL.

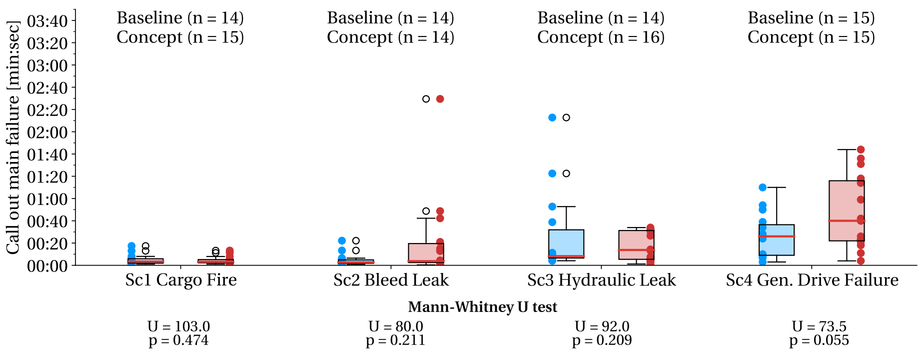


Figure 6.10: A comparison between the baseline and concept displays for detection time during each scenario.

Checklist completion time

The time spent on the checklists is also an important factor for the performance of the displays, specifically the ATD. The ATD presents the same action steps, but the notes are presented as operational impacts in a centralized location on the FSSD and ATD. Figure 6.11 shows the time spent on checklist execution and reading. Obviously, the more checklists were completed, the more time was spent. As the figure shows, many significant differences were found. The concept displays resulted in less time in scenario 1 and 3, while in scenario 2 and 4 the exact opposite happened.

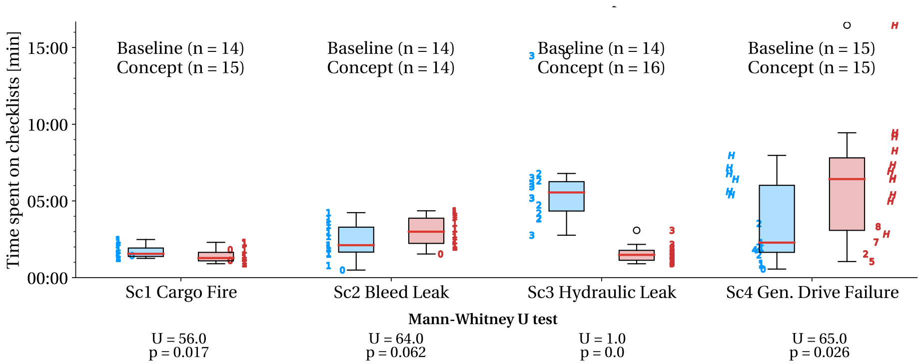


Figure 6.11: A comparison between the baseline and concept displays for the time spent on checklists during each scenario. The time spent on checklists depend on the number of checklists completed. The number of completed checklists are indicated with a number instead of a circular marker and with an offset on the x-axis, fewer completed checklists are plotted closer to the box plot. The H-marking indicates that 10 or more checklists were completed.

6

The biggest difference is found for the hydraulic checklist, which is heavily populated with notes. The ATD leaves these out and presents it on FSSD and ATD as operational alerts. In the ECL, overridden items remain visible after a certain condition is confirmed. This is not presented in the ATD. This made the pilots who used the concept displays a bit faster, approximately 20 seconds, in the first scenario.

In the bleed leak scenario, some pilots waited to let the duct cool down, before trying to switch it back on. The pilots that used the concept waited more often. This step is not mentioned in the checklist and is clearly a result of the training they received in the past.

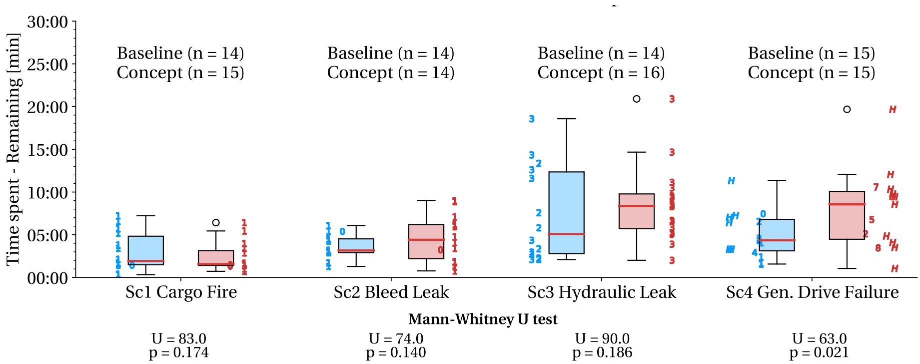


Figure 6.12: A comparison between the baseline and concept displays for the time spent on creating a decision during each scenario. Here, the number of checklists are marked with a number and proximity to the box plot, similar to Figure 6.11 and Figure 6.10.

Decision time

The decision time needed by the pilots was derived by subtraction the time without failures, the detection time, and the checklist completion time from total run time, as presented in Figure 6.12. It is therefore not only decision time, but also time in which they scanned the cockpit to gain awareness.

This data shows one significant effect, which is for the fourth scenario. It took the pilots more time to decide with the concept displays, on average 3 minutes more. In scenario 2 and 3, the data hints to, although it is not significant, that the pilots with the concept displays took approximately 60 seconds longer to decide compared to the baseline display group.

Therefore, these results differ from what was hypothesized in H_3. In fact, the pilots who used the concept displays were slower in deciding on the remainder of the flight after a non-normal event. This could be partially explained by the amount of 'new' information. The concept showed all the impacts and, hence, more factors needed to be considered in the decision, which take time. The baseline displays did not present these factors and were as a consequence often not taken into consideration.

6.4.3. Usability

User's Experience

An important part of this experiment was also to test the users experience and opinions about the concept displays. Most of the pilots were either somewhat positive or extremely positive towards the concept. It would further increase, to their opinion, the level of flight safety.

The majority liked the Horizontal Situation Display (HSD), Alerting and Task Display (ATD), Functional System Status Display (FSSD), and Vertical Situation Display (VSD) either 'somewhat', or 'a great deal'. The TVSD was the least preferred display element. It was also used (in these scenarios) the least, followed by the VSD. It might be because it is a quite unconventional display and requires some time to get used to. Although the presented scenarios included some time constraints, in more dynamic scenarios in which speed limitations and time slots given by ATC support given by the TVSD might be more relevant.

Furthermore, the pilots indicated that they really liked the visual representation of airspace. However, they commented that these indications could influence decisions too much. An airport within a colored area might be discarded too soon as an infeasible option. They found it difficult to obtain information what the colored spaces and airport conditions were based upon.

Errors

The errors made during the checklist execution phase are an indicator on how well a display performs. The count of incorrect checklist executions is presented in Table 6.5. Two types of errors are observed. The first type occurred during the usage of the checklist. The ECL used in this simulation did not have automatic selection for the conditional items (choice items) in which pilots needed to choose one of two options, for instance: 'Both WING-BODY OVERHEAT lights illuminated'. In total, 4 mistakes were made with these types of steps, ending up in a completely different situation. For exam-

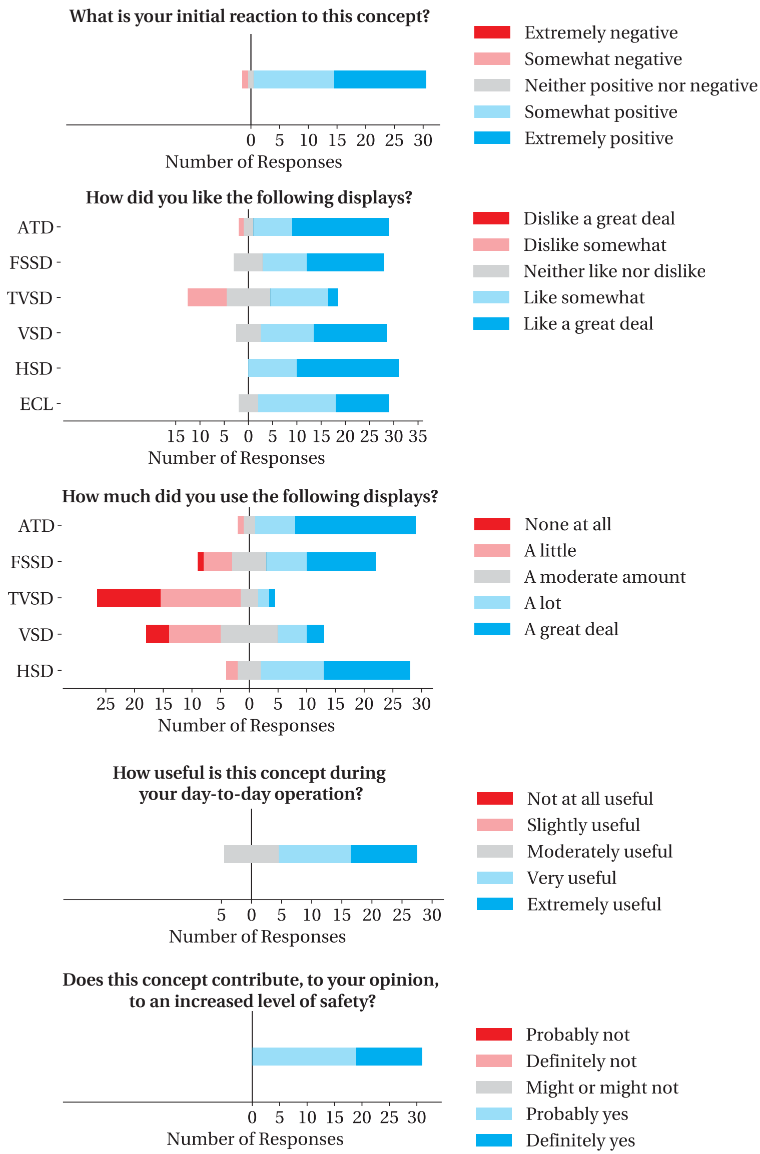


Figure 6.13: User responses to the post-experiment survey. Capturing the initial reaction, preferences, usage, usefulness, and contribution to safety of the concept. The displays are as follows: Alerting and Task Display (ATD), Functional System Status Display (FSSD), Time and Velocity Situation Display (TVSD), Horizontal Situation Display (HSD), Vertical Situation Display (VSD), and Electronic Checklist (ECL)

ple, trying to solve a case in which both air-conditioning packs are inoperative instead of one.

The other type occurred during the execution phase —the actual toggling of the controls. In total, 5 slips were observed. For instance, some participants toggled the wrong switch, for instance the left switch instead of the right one. These errors were observed on both types of displays and no difference, between the displays was found.

Table 6.5: Errors made during the checklist execution.

	Baseline	Concept	Total (n=128)
Choice errors	2	2	4 (3%)
Action errors	2	3	5 (4%)
Total errors			9 (7%)

6.5. Discussion

The results show that the operational alerting prototype enhances informed decision-making, however, a reduction in workload was not observed. The working principles to translate the aircraft states and environmental states into one single visualized operating environment helped to increase awareness and supported making more informed decisions. Translating areas that were prescribed in text to a visual form helped pilots to interpret hazards more accurately.

6

The presented SIGMETs in the experiment are not uncommon, in fact, they can be encountered frequently in daily operations. However, some participants had difficulty with interpreting these codes. Some pilots who used the baseline displays interpreted the messages as everything north of the latitude 46 degrees north was affected by icing (in scenario 2 and 4), or everything west of the longitude 101 degrees west was affected by turbulence (in scenario 3 and 4). This interpretation is incorrect if the SIGMETs are strictly followed since the conditions only apply within the announced FIR and do not extent beyond. The boundaries of the FIR were in the experiment often not understood nor taken into consideration. It might, therefore, be clearer to use coordinates instead in SIGMETs, or more effective, to present them integrated on a map, as was done in the operational alerting concept. Pilots already rely on the FMS to translate these coordinates, however, plotting these coordinates is time consuming. Presenting the messages as spaces makes interpretation of such information easy and the participants of the experiment liked this a lot. This idea of presenting the SIGMETs in a visual form on a map is not new, though presenting them integrated with the aircraft's state has not been done before. And translating a recommendation as 'avoid icing conditions' into the actual to-avoid areas proved effective. This does not only apply to icing areas but also to turbulence, and to limitations from the aircraft itself (e.g., a reduced ceiling).

Another observation was that pilots who used the concept displays were more involved in (re)planning. They planned visually by pointing to the display where they wanted to go, which shows that their mental model is supported externally. The participants with the baseline did not show this behavior. Hence, the operational alerting displays can also be of value as a (co-located) crew communication tool.

An observed negative aspect of presenting areas with a color coding is that it strongly steers the user's decisions. Although the purpose of the concept is to alert, areas can be interpreted as hard physical boundaries. However, in the case of turbulence it is unlikely that the severe turbulence would be encountered in the entire FIR (i.e., following the exact boundaries of a FIR). The location of the turbulence is an estimate. The large colored areas might present the real situation worse than it actually is, and the pilot might be inclined to change course without any necessity. Pilots mentioned that in the real operating world these areas are often conservatively presented, and crossing is often possible. This interpretation of inaccuracy could be added to the displays to soften the boundaries.

During the experiment, some evidence appeared that pilots were over-trusting the system. Complacency was specifically noticed with the landing distance calculation. On multiple occasions, the participants assumed that the presented distance was true, without understanding the actual causes. This disconnect can be dangerous and can lead to surprises at a later stage of the flight. Efforts should be spent, in the (re)design, to engage the pilot with this crucial part of the flight. For example, by making a stepwise procedure that needs to be confirmed, or with better labels stating the reason of a color coding.

The clarity of the labels could be improved since in some cases the participants did not fully understand why some items were made orange. This should be clear from the start, otherwise users will make up why a certain area is color coded —often for the wrong causes.

It was hypothesized that less time would be spent on deciding since all information was transformed and acquired by the prototype. However, this was not the case. In fact, the more constraints one observes the more time it takes to make a decision. This was understood when a student, without any flying experience, tried out a run. This student was not familiar with flying, nor with the limitation that pilots face; and formed a decision in a split second based on the orange color-coded symbols. This brief example indicates that the more experience one has, more needs to be envisaged, which slows the person down. However, the overall total run time was not negatively influenced by the concept, with the exception for the fourth scenario where the pilots with the concept displays completed more checklists and thus spent more time.

Scenarios with time pressure could show the potential benefit of the prototype. In this experiment, the participants were given all the time they wanted. If time is limited, the result might be different. Nevertheless, spending more time, if time is available, to formulate a decision and carefully reconsider all options is trained. This training practices helped some pilots to systematical handle the non-normal events.

This experiment showed that pilots interpret the same conditions in many ways (e.g., the NOTAM stating the firefighting category or the location of icing areas). This shows the added value of a second crew member. Two pairs of eyes and brains seem to be an additional safeguard against incorrect assumptions. The question remains if this error-checking mechanism can ever be replaced by an information system. The combination of two pilots and an information system, such as the operation alerting support, might be the most robust solution to resolve non-normal events and counteract incorrect assumptions.

The concept was limited to relatively static scenarios. A failure just after take-off, or in the approach phase, might be more interesting to test the VSD or TVSD. Furthermore, no replan possibilities were built in. Pilots could, therefore, not evaluate their newly planned path. This might have helped them to understand impacts on fuel and or the proximity of terrain. By 'drawing' the new path, a direct feasibility check can be provided.

In this experiment, much of the measurements relied on what the pilots said out loud. If they did not say what they thought; no conclusions could be drawn. However, the pilots were motivated and spoke a lot. Another limitation that was observed is the backlight of the displays that presented the physical alerts, buttons, and selectors. Alert lights in real cockpits are brighter and the contrast is higher. The lower contrast possibly made detection slower. This effect can become an issue if alerting relies primarily on screens on the flight deck.

Although the concept increased the number of informed decisions, there is still room for improvement. Improvements for the concept can be made to enhance performance in the detection phase. The ATC datalink messages and system failure were sometimes detected late or not at all. One solution to solve this could be to make the pilot confirm the messages that are causing the change of areas, although, this causes a negative impact on workload.

Furthermore, the color coding applied to the airport symbols should also be more salient. The airport and runways conditions need be made more explorable and self-explainable.

Next, workload and errors in the checklist execution phase can be reduced by automating the system management steps (e.g., automatically configuring the systems as prescribed by the checklists). Multiple mistakes were made with the checklist execution, which were easily avoidable. However, this automation can only be applied if the effects on the operation are clearly alerted. Therefore, the redesign should focus primarily on linking the presented spaces with the system failure or changed environmental condition. At a later stage, the system management tasks could be automated. The pilots will then be left with the operational alerts, and thus increasing well-informed decisions and reducing workload.

6.6. Conclusions

This study aimed to quantify the effectiveness of the operational alerting prototype. The number of informed decisions was used as a measure for the quality of the information transmitted by the display. For the new concept displays, the number if informed decisions were higher.

The working principle of the concept displays is that it alerts impacts in the same format as the flight plan (i.e., as the abstract elements of path and space). The concept displays presented the impacts on the flight plan as reduced spaces, and 'broken' paths. The pilots were able to make more well-informed decisions with this information presentation and thus can be concluded that the transformation of system states and environmental conditions into space and path effects is effective. The pilots indicated that they liked the displays to a great extent, and that the concept displays would contribute to flight safety compared to the current standard. However, further improvements can be made to improve detection and interactivity.

This study proved that the chosen ACWA method can indeed result in an effective design. The translation of alerts to space and paths impacts provides better awareness. Hence, these results pave the way for enhanced support tools on the flight deck. Integrating environment and the system state information are providing an external mental support, which makes comprehension of the system capabilities and impacts easier. However, over-trusting the indications proved to be a concern with this type of displays, a critical attitude of the operator will be required.

The experienced workload nor the total run completion time did not decrease significantly, instead, remained similar. Hence, more effective reductions in workload can be achieved when other tasks are automated, for example, the system reconfiguration task.

The results of this study indicate that alerts based on spaces and paths proved to be an effective decision support tool. Flight-deck interfaces which present such operational alerts result into more well-informed decisions, which brings the recently proposed Reduced-Crew Operationss (RCOs) on step closer but can also be beneficial for the conventional crew complement.

References

AAIB (2010). *AAIB Bulletin: 9/2010 SE-RHX EW/C2010/05/01*. Technical report, Air Accidents Investigation Branch.

Australian Transport Safety Bureau (2013). *In-flight uncontained engine failure A380-842, VH-OQA*. Technical Report AO-2010-089, Australian Transport Safety Bureau, Canberra.

Bailey, R. E., Kramer, L. J., Kennedy, K. D., Stephens, C. L., & Etherington, T. J. (2017). An assessment of reduced crew and single pilot operations in commercial transport aircraft operations. In *AIAA/IEEE Digital Avionics Systems Conference - Proceedings*.

Bainbridge, L. (1983). Ironies of automation. *Automatica*, 19(6), 775–779.

Boeing (2005). *737-600/-700/-800 Flight Crew Operations Manual*. Seattle, Washington, USA: The Boeing Company.

Boorman, D. (2001). Safety benefits of electronic checklists: An analysis of commercial transport accidents. In *Proceedings of the 11th International Symposium on Aviation Psychology* (pp. 5–8). Columbus.

CAE (2017). *Airline Pilot Demand Outlook: 10-year view*. Technical report.

Elm, W. C. & Potter, S. S. (2003). Applied Cognitive Work Analysis: a Pragmatic Methodology for Designing Revolutionary Cognitive Affordances. *Cognitive Task Analysis*.

Endsley, M. R., Bolte, B., & Jones, D. G. (2003). *Designing for Situation Awareness: An Approach to User-Centered Design*. CRC Press.

Faulhaber, A. (2019). From Crewed to Single-Pilot Operations: Pilot Performance and Workload Management. In *20th International Symposium on Aviation Psychology* (pp. 283–288).

Frost, L. (2021). EXCLUSIVE Cathay working with Airbus on single-pilot system for long-haul.

Harris, D. (2007). A human-centred design agenda for the development of single crew operated commercial aircraft. *Aircraft Engineering and Aerospace Technology*, 79(5), 518–526.

Pilot Institute (2020). Women Pilot Statistics: Female Representation in Aviation.

RNSA (2018). *Final Report on Aircraft Serious Incident 18-104F018*. Technical Report 18, Icelandic Transportation Safety Board.

Transportation Safety Board of Canada (2018). *Air Transportation Safety Investigation Report A18W0081*. Technical Report January, Transportation Safety Board of Canada.

Woods, D. D. (1984). Visual momentum: a concept to improve the cognitive coupling of person and computer. *International Journal of Man-Machine Studies*, 21(3), 229–244.

7

Discussion & Conclusions

Increasingly automated systems are frequently cited as one of the essential enablers for Reduced-Crew Operations (RCO), though the implementation details remain unclear. This study aimed to address this gap by proposing a solution for workload reduction and decision-making supports for pilots, with the goal of maximizing human capabilities under the challenging conditions introduced by RCO, which could also be advantageous for current two-pilot crew operations.

This study examined two strategies for assisting crews on commercial flight decks. One approach aimed to reduce workload by fully automating seemingly redundant tasks, such as system management tasks, while the other sought to enhance support for flight plan management to enable more informed decision-making.

More specifically, the first part of this study focused on elevating the Level of Automation (LOA) of the system management function from *Step-by-Step Action Support (D2)* to *High-Level Support of Action Sequence Execution (D4)*, as illustrated in Figure 1.2 (see also Appendix A for the definitions).

In the second part of the study, the LOA of the flight plan management function was elevated for the information acquisition stage, moving from the current levels *Manual Info Acquisition (A1), Artifact-Supported Info Acquisition (A2), or Low-Level Automation Support of Info Acquisition* to *Full Automation Support of Info Acquisition (A5)*. For the information analysis stage, the level was elevated from *Working Memory-Based Info Analysis (B0)* to *Full Automation Support of Info Analysis (B5)* type systems, where applicable (see Figure 1.3). However, the decision-options are deliberately generated by the human operator.

Both proposals were prototyped and evaluated through human-in-the-loop experiments. The effects and impacts of this increased automation are discussed in relation to the guiding questions outlined in Chapter 1.

7.1. Discussion

Guiding question 1

What are the human performance challenges related to flight plan management and how is this supported by current flight deck systems?

The main challenge identified for flight crews in flight plan management is the lack of support for understanding and anticipating the *impacts* of disruptions during both the information acquisition and analysis stages. This issue is discussed in Section 2.2.4 and was confirmed by the experiments conducted.

The challenge in the acquisition stage is not the lack of information, but rather managing the substantial volume of data and the distributed nature of sources and artifacts. Additionally, this information often needs to be decoded to be useful. Pilots would benefit from having this operationally relevant information presented in a more accessible format. In the short term, airlines, aeronautical data providers, and aircraft integrators should enhance their current artifacts by introducing filtering and highlighting options based on the operational context in an easy accessible application to replace several large documents with cryptic codes. Specifically, decoding and visually presenting geographical information was found to be very effective for pilots to quickly identify potential impacts (see Chapter 6), and allowing them to focus on generating contingency plans.

The challenge with the information analysis stage is its heavy reliance on the crew's working memory, airmanship, intuition, and past experiences. Ensuring consistent performance across a company's workforce is consequently difficult, with distractions and concurrent tasks on the flight deck and the quality of training being key influencing factors. As a result, maintaining or improving safety levels depends on extensive, time-consuming, and costly training for operators. Implementing information automation support can help reduce this dependency.

If, in the future, there is a desire to reduce dependency on training and make pilot behavior more consistent across all operators, a change to the current support systems is recommended. Presently, flight deck supports heavily focus on aiding the pilot as a system manager rather than as a flight plan manager. A key responsibility of a modern airline pilot is to continuously integrate and evaluate environmental conditions alongside the aircraft's capabilities to assess whether the planned operation remains feasible. Gathering, combining, and projecting all relevant information during disruptions is challenging for a conventional crew of two, let alone for a single pilot.

Recently introduced systems, such as overrun protection systems, address this need by alerting pilots when a landing is deemed unsafe. However, a broader flight deck approach should be adopted to support the pilot throughout the entire flight. Not only could the flight deck support systems be adjusted, but electronic flight bags could also provide valuable assistance by transforming current environmental and operational information, such as Notice to Airmen (NOTAM) and weather reports, into more usable action-oriented formats.

When implementing operational alerting across the broader flight deck, it is crucial to keep the pilot actively involved in the decision-making process. Pilots should formulate contingency plans themselves to remain engaged and avoid complacency. This might be one mitigation to overreliance on generated, potentially faulty, flight paths by automation. However, distinguishing between highly reliable and less accurate information will be become very challenging for pilots if all are presented in a single display. Of course, inaccurate information sources should either be avoided or improved, but this is not always feasible. In general, critical thinking should be emphasized during pilot training. Furthermore, there is a risk that introducing inaccurate information could undermine trust in the entire system, which can have grave consequences. Another risk is that the crew may become overloaded if the display becomes too cluttered, which could jeopardize the effectiveness of the entire display.

Integrating operational information and highlighting impacts may also lead to skill degradation in the long term (e.g., inability to use the original source). However, it can be argued that the benefits of providing a constant view of potential contingencies will make the crew more creative and more engaged in operational decision-making.

The least experienced pilots are expected to benefit the most from operation alerting, as they will have access to an extensive knowledge base from the start, which typically takes years to develop with current support systems. Hence, the benefits should outweigh the adverse effect of skill degradation.

Another approach to address the challenges of flight plan management is to reduce the time required for other tasks, such as system management tasks, thereby freeing up time, and reduce distractions to focus on understanding the impacts. However, no evidence was found for this, as discussed further with the next guiding questions.

7

> **Guiding question 2 & 3**
>
> What are the potential gains in terms of task reduction for the envisioned system management automation? And what is the impact on human performance if system management would be increasingly automated?

Based on a Boeing 737 NG Quick Reference Handbook (QRH), nearly 39% of the checklist items were identified as potential candidates for automation, which reduces the average number of steps per checklist from 6.5 to 4. The remaining checklist steps primarily concentrate on supporting aviate and flight planning activities, which are the pilots' main responsibilities and crucial for maintaining proficiency.

The experiments with the conservative, batch approval, automated checklist concept showed that the time required 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 time saving of 3 minutes and 51 seconds and 1 minute and 48 seconds, respectively. It is noteworthy that the achieved time reduction measured in the experiment closely aligns with the initial task reduction prediction. Hence, task load reduction gains through simple task allocation seems to be useful for preliminary design quantification.

Automating the system configuration steps did not noticeably affect decision quality. However, it significantly reduced the time required to make decisions. This improvement may be attributed to automation providing participants with quicker access to relevant flight plan information and reducing clutter, which likely facilitated faster comprehension and more efficient decision-making.

This provides again evidence that the existing information in checklists could be enhanced and more targeted to better support the quality of operational decision-making. Providing additional guidance on what defines a 'suitable' airport during specific non-normal events could be particularly beneficial. In that case, decisions will be well informed and faster compared to current information.

The experiments revealed that workload experienced by pilots did not significantly change. System configuration tasks are generally not cognitively demanding and tend to involve rule-based execution rather than higher cognitive effort. Therefore, eliminating these steps did not have a noticeable impact on workload. To effectively influence workload, efforts should be directed toward simplifying knowledge-based tasks. For instance, supporting the pilot in understanding when, where, and how the flight plan will be affected. Note that the concept was tested only with two non-time critical failure conditions. To get a more complete prediction of the impact of this automation, the concept also should be evaluated with scenarios under high workload conditions.

It can be argued that system knowledge might diminish if no direct interaction with the system is required, though whether this is detrimental is open for discussion. Given the increasing complexity of modern aircraft, fully comprehending all aspects of the system, especially under high-stress situations, can be challenging or even impossible. Improving system knowledge can be achieved with providing more training, or instead providing better indications to effectively communicate how malfunctions or system capabilities impact the pilot's main tasks, such as aviate, communicate, and flight plan management. Therefore, an elevated level of system automation should always be accompanied by an enhancement of decision support systems, as proposed in this thesis.

Automating system configuration steps not only reduces workload but also minimizes configuration errors. This has been observed as pilots sometimes fail to select a correct checklist condition or incorrectly configure parts of the system (see observations from Chapter 6). However, these errors are not simply mitigated with automation as they will be moved to the designer of the system.

Noticeably, the trend in modern airplanes is toward automating more system management tasks. However, the effectiveness of this automation can be influenced by the type of switch used. Although the underlying system may handle tasks automatically, the crew often still needs to manually align switches with the system's status, diminishing the benefits of automation. Currently, many aircraft use toggles, levers, handles, or selectors that do not switch automatically. As a recommendation for newly designed airplanes, switches should be designed to reflect the system state without requiring crew interaction if the function is intended to be automated (e.g., through displays or actuated switches). This approach will also support remote-controlled operations, as proposed by various Single-Pilot Operations (SPO) Concept-of-Operations (ConOps).

The system management function LOA was upgraded from *Step-by-Step Action Support (D2)* to *High-Level Support of Action Sequence Execution (D4)*. However, given the limited impact on decision-making quality and the experienced workload, this level could potentially be further advanced. For instance, to *Full Automation of Action Se-*

quence Execution (D8), where the system initiates and executes a sequence of actions and the human cannot monitor nor interrupt it until the sequence is not terminated. In this case, more time can be allocated to informing decisions and fewer distractions will be introduced. However, it is essential to enhance operational decision-making support accordingly. Depending on the implementation of this support, decisions could then be made more quickly and with better information.

Guiding question 4

What information is needed to effectively support operational decision making?

Effective support requires information that aligns with the user's goals and the relevant factors within the problem space. However, presenting too much information or irrelevant information can lead to clutter and overwhelm the user. Structuring information according to abstraction levels and system goals appears to be an effective strategy for condensing and identifying the relevant information.

The Applied Cognitive Work Analysis (ACWA) method was used to systematically capture the work domain, user goals, functions, and abstract elements. This method applies a stepwise approach to derive requirements from these goals and abstract components. The stepwise methodology has proven to be effective and practical, providing traceability that is often difficult to achieve with methods such as Ecological Interface Design (EID), where the connection between the Abstraction Hierarchy (AH) and the Skill, Rule, Knowledge (SRK) taxonomy can be unclear (McIlroy & Stanton, 2015). Furthermore, ACWA supports reusability, ensuring that if the visual representation does not meet user interaction or perception needs, the core cognitive work requirements remain valid and applicable.

ACWA was introduced to be an pragmatic method for application in industry. However, additional guidance and examples would benefit new practitioners. Constructing a Functional Abstraction Network (FAN) —the initial step in the ACWA method— can be challenging. It was helpful to focus on the 'commodities' being managed and the factors that influence them (i.e., what creates or destroys the commodity).

Even though the FAN is not widely adopted, it has proven to be a highly effective tool for organizing large amounts of information. The FAN has been found to be more effective than the Abstraction Hierarchy (AH) due to its elimination of the abstract layer, which is inherent in each block in the FAN, its transition from a hierarchical to a network structure, the inclusion of goals per function, and its flexibility to incorporate non-physical commodities. It encourages practitioners to consider the system's goals, the abstract elements or 'commodities' being controlled, and their interconnections, which aids in a comprehensive understanding of the work domain. Naturally, other modeling methods can also achieve similar results. However, for the analysis of large work domains the FAN is recommended over a AH.

The primary abstract elements relevant to the flight crew during air transportation, as identified using the FAN, are the commodities of paths and spaces (in time). These paths and spaces can be created or removed during air, ground, and passenger maneuvers. Functions such as flight control and thrust management (propulsion) influence the creation and destruction of these paths and spaces. For instance, operating more fuel-efficiently results in a slower reduction of the operating space compared to less efficient operations. Additionally, factors such as terrain affect the available space. Each aircraft has unique capabilities that produce distinct paths and operating spaces, which align with higher-level goals such as ensuring safety, maintaining compliance, adhering to schedules, minimizing costs, and maximizing comfort.

These abstract elements can be applied to various transportation domains, including maritime and road transport. Hence, the model presented in Chapter 4 can serve as a starting point for many new supporting systems. Especially, Figure 4.2 forms a foundation that can be enhanced with more detail, but the fundamental commodities will not change.

To make ACWA more accessible to new practitioners, a dedicated requirement tracking tool that integrates the FAN editor and includes additional example material could help attract a larger audience. However, it is crucial to note that the ACWA method does not inherently ensure an effective interface, as overall system performance heavily depends on effective visualization and interaction with the display. This is where the expertise of UI and UX designers becomes essential. Therefore, the ACWA method should be used to determine *what* is displayed rather than *how* it is presented.

Guiding question 5 & 6

What would the flight deck look like if it would focus on supporting operational decision making? And what is the impact on human performance if the pilot is provided with this operational decision-making support?

According to findings from ACWA, pilots would be better equipped to make informed decisions if they had a clear overview of the *impacts* on the current flight plan. By presenting not only these impacts but also the boundaries of the operating space and paths for each goal, pilots can more effectively plan to meet all operational goals.

The proposed concept included horizontal, vertical, and speed-distance displays to represent impacts across all dimensions. Converting cryptic, text-based impacts into visual elements significantly improved the information-gathering process. With a single glance, operators could identify where impacts were affecting their operation. Pilots using these visual displays made more informed decisions, although their final decision was largely influenced by experience, trust, and risk aversion. Nonetheless, pilots who were presented with the impacts were better prepared and more aware of the risks they were taking, which is acceptable if they will be the ultimate decision-makers and willing to take these risks.

However, based on the experiment conducted and presented in Chapter 6, the visual indications did not necessarily expedite decision-making; in some cases, they actually *prolonged* decision time due to the increased number of impacts considered. Pilots using baseline displays evaluated fewer operational impacts, which affected the quality of their decisions. Therefore, faster is not always better. Decision-making involves balancing speed and thoroughness, and these concept displays facilitate a decision to be made with more thoroughness. In the scenarios tested, pilots were not under time pressure, and the outcome might have differed under high workload conditions where there was insufficient time to translate text-based impacts into a comprehensive overview without aids. Additionally, while the simulation was designed to be as realistic as possible, certain limitations should be noted (see Chapter 6).

Besides the improvement in informed decisions, pilots generally liked and found the concept useful for their day-to-day operations. However, the time velocity display was not as well received, indicating that it may currently be too theoretical or lacking a clear use case. Exploring alternative presentations or evaluating scenarios where time and speed restrictions significantly impact operations would be beneficial (e.g., during required time of arrivals scenarios in combination with en-route weather)

Pilots were observed to be more actively generating options using the concept displays, such as pointing to navigate around or over certain airspaces. This aligns with the intended role, demonstrating that pilots are actively engaged and 'in the loop.' This engagement is likely to enhance proficiency in contingency planning in the long term, which was a key objective of the design (see Chapter 1).

The experiment also showed that pilots presented with coordinates, such as done in SIGMETs, were often not capable of determining where hazardous areas like icing and turbulence were located. This emphasizes the difficulty of working with 'raw' data and suggests that to make the geographical information provided by NOTAMs and SIGMETs more usable, a visual representation should be provided.

Although the displays proved beneficial, they can still be optimized. For instance, adding text labels to more explicitly explain why paths and spaces are impacted would be advantageous. Without this information, pilots might start guessing the reasons for the impacts, leading to confirmation bias, where they interpret the indications according to their existing beliefs, which are not always accurate. It was also observed that some pilots avoided certain airports solely based on amber color coding, without being able to explain why those airports were considered less feasible. This suggests an over-reliance on the automation. Automation complacency is a serious concern if the information is inaccurate or if not all conditions are considered. However, given that crews had limited exposure to the displays, additional training could improve their understanding of the impacts.

Therefore, pilots need to be trained to be critical, especially the few less experienced pilots were easily influenced by a color-coding. A note of caution is due here since this is based on a few observations, which cannot be seen as statistical evidence, but is something to consider for future research. The critical attitude, or trained to be critical, might come with experience. It is important to note that in the evaluated prototype, pilots had no easy way to verify why certain areas were highlighted. Making the underlying causes more discoverable through direct manipulation could assist in verifying these conditions (e.g., by clicking on the area to understand the reason).

This concept necessitates a revolutionary change to the flight deck, which inherently involves some risk. Additionally, this change will require pilots to undergo (re)training, and new procedures will need to be established. Consequently, this concept could first be introduced on a smaller scale, such as in general aviation or unscheduled operations, before being gradually adopted by commercial operators. These operations will likely benefit most from the concepts since these operate in more remote and dynamic environments.

Furthermore, the proposed concept requires much information integration. Information about the environment, airline operating procedures, the aircraft, and the pilot's intent all need to be combined. This is a challenge by itself. However, the aircraft can serve for example as a data hub that interfaces with the EFB in a standard way to present the flight plan and the impacts on it in a standard way.

Currently, the displays were primarily used for evaluating impacts rather than resolving them. Potential improvements could include direct manipulation though touch capabilities to interact with the flight plan to mitigate impacts or to interact with spaces to address issues (e.g., activating icing systems and therefore 'opening' up spaces).

As proposed in this study, the flight plan management LOA was elevated for the information acquisition and analysis stages, leading to more informed decisions and greater pilot engagement in contingency planning. Elevating the LOA for the decision-making stage, however, could potentially introduce 'out-of-the-loop' behavior and reduce critical thinking. Therefore, a combined approach is recommended: automating the system management function to handle all tasks that do not directly influence flight path management (D8), while maintaining the proposed levels for information acquisition and analysis stages. This approach is expected to improve decision-making quality and either reduce or maintain similar non-normal event resolution times. Something to be investigated by future research.

7.2. Conclusions

This study was intended to achieve the following research objective:

7

> **Research Objective**
>
> Enhance the modern commercial flight deck, by elevating the Level of Automation (LOA) on system management and flight plan management, to reduce workload while improving decision-making performance.

The two conceptualized automated supports with elevated LOA, as separate systems, reduced workload and enhanced decision-making performance by reducing the checklist completion time and increasing the number of informed decisions.

The most significant findings to emerge from this study are:

- Automating approximately 40% of the tasks in the QRH —exclusively system management tasks— resulted in a similar reduction in time, without negatively affecting informed decision-making. Consequently, the information presented could be further enhanced to support more informed decision-making.

- Several, though relatively few, pilot errors were observed during the system management task, such as switching the incorrect air conditioning systems or checking the wrong electronic checklist item. This highlights the need to either reduce such tasks or eliminate them entirely to minimize the likelihood of errors.

- Flight crews are unable to reliably encode the 'raw' information from sources such as Notice to Airmen (NOTAM) or SIGnificant METeorological information

(SIGMET) while flying and support is required to translate coordinates into a visual depictions (e.g., on a map-like display).

- Alerting at the flight plan level (i.e., operational alerting) has proven to be effective and well-received by pilots. Pilots who received operational alerts detailing where and when impacts were expected made more informed decisions, were more actively engaged in replanning, and considered a greater number of options.
- Confirmation bias became apparent when pilots began interpreting and explaining the color-coded flight deck effects on the displays according to their preexisting beliefs, which were not always accurate. This underscores the need for clear labeling and explanations for color codes, as well as fostering critical thinking to mitigate such biases.
- Pilots perceive risks and hazards differently based on their individual experiences. These experiences significantly influence their decision-making outcomes and the level of trust they place in alerts and indications.
- The Applied Cognitive Work Analysis (ACWA) offered a well-structured yet pragmatic framework for organizing goals and translating abstract elements into traceable requirements. Describing impacts in terms of space and path effects across multiple domains, such as payload, ground, and flight operations, has proven effective. Additionally, the Functional Abstraction Network (FAN) can be adapted and reused by various systems that focus on specific aspects of the model. Moreover, reasoning in space and path can be beneficial for all transportation domains and the FAN can be seen as a design template for these domains.
- The design of visual elements depends on the expertise of visual and interaction designers, and no design can be deemed perfect. However, with the requirements derived from the ACWA, there is a common objective basis for the design, which allows for the verification and assessment of displays.

7.3. Recommendations

As pointed out before, future efforts should focus on combining a 'Full Automation of Action Sequence Execution' (D8) type system management and flight plan management supports as presented in this study into a single concept. This integrated system is likely to reduce workload and enhance decision-making performance. Future research could also focus on enhancing support for the re-planning and execution phases of contingency management. This could potentially lead to more task reduction.

Next-generation flight decks should focus on further enhancing the flight management function, as pilots increasingly take on the role of flight plan managers. Flight plan management support should be prioritized with a dedicated display that helps the crew store, explore, and organize the effects of potential disruptions —both internal and external— on the flight plan.

A significant concern that needs to be addressed is how to manage the integration of reliable internal (system) information with potentially unreliable external information for operational alerting, as this may undermine overall trust in the system. Unreliability can be caused by information that is outdated or inaccurate. Future efforts should focus on improving the reliability and accuracy of external data or developing methods to effectively manage unreliable data, while critical thinking should be a focus point during pilot training.

The flight planning displays were tested under quasi-static conditions (i.e., cruise at altitude). The next step is to evaluate these displays in dynamic, time-critical situations, such as approaches with weather and traffic. In such scenarios, where there is limited time for traditional information searches, pilots could benefit from the new decision-support tools by interpreting information more quickly, likely leading to more informed decisions compared to baseline displays. Evaluations should include scenarios involving airspace time slots, speed limitations, and airport operating hours, as these will effectively test the capabilities of the TVSD and the FSSD.

Although ACWA has not received extensive attention from researchers or industry, this study found it to be highly useful for encapsulating extensive domains, such as 'commercial flight operation', into a single, manageable model. The pragmatic stepwise approach of ACWA is particularly valuable for its traceability and scalability. Integrating ACWA into a graphical modeling and requirement tracking tool and providing additional examples would further enhance its adoption and utility.

Design iterations are necessary for each display, as outlined by ACWA. This concept was the result of the first iteration. Next iterations should address issues related to the 'why' of impacts. For instance, labels could be added to clarify the reason behind color-coded areas or paths, as requested by the pilot.

Regarding RCO, the developed systems can be utilized both on the flight deck and at ground stations. By providing all involved parties with a unified 'operational' view, decisions can be shared among multiple stakeholders. The concept displays can serve as a collaborative tool, enabling communication in the language of the flight plan (i.e., space and paths). Airports or specific flight plan elements can be highlighted or flagged for resolution by specialists with more accurate information. Thus, this operational decision support can facilitate collaborative decision-making, making it a valuable area for future investigation.

In conclusion, this study demonstrated that system tasks can be effectively allocated to automation without severe negative impacts as long as in-flight contingency planning is supported. This study further emphasized that all types of commercial operations —regardless of crew composition— can benefit from more integrated, accessible, and accurate information for in-flight contingency planning. However as Chapters 3 and 6 revealed, enabling Single-Pilot Operations (SPO) introduces risks due to the tendency of pilots to make and adhere to incorrect assumptions. Having a crew member who critically verifies and challenges these assumptions serves as a simple yet effective safeguard against this issue. A two-pilot crew, with both different perspectives, cognitive resources, and knowledge bases and experiences, is generally more reliable than a single pilot, regardless of the support systems in place.

References

McIlroy, R. C. & Stanton, N. A. (2015). Ecological Interface Design Two Decades On: Whatever Happened to the SRK Taxonomy? 45(2), 145–163.

Acknowledgements

First and foremost, I am deeply grateful to **Rene van Paassen** and **Clark Borst** for their invaluable guidance, patience, and unwavering support throughout this project. Their extensive expertise, along with the trust, enabled me to explore directions that ultimately led to the success of this work. Their mentorship has been truly instrumental, all delivered with a sense of fun and excitement. I truly enjoyed hacking a working flight simulation together with Rene. Working with the SIMONA taught me so much about linux, real-time simulation, and python skills I'm using on a daily basis. It made me believe that everything is possible as long if you put your mind to it. Clark's guidance was always spot-on, and I still miss the lively lunch conversations, where we discussed essential ground-braking research and "documentaries" such as *The Terminator*, providing just the right distractions to recharge and press on.

I would also like to extend my gratitude to **Max Mulder** for his constructive feedback, continuous support, and for giving me the opportunity to pursue this unique project. His insights and encouragement were pivotal to the progress and success of this research.

Special thanks go to **Dirk van Baelen** for his critical assistance in setting up the connection with DUECA and the custom simulation modules, establishing the technical foundation for this work. I am also grateful for the memorable trip to the summer school in China, which made this collaboration even more enriching.

My sincere thanks to **Coen Linskens** for his excellent work on the automatic checklist. His quick grasp of complex concepts, especially amid the unique challenges of the pandemic, significantly contributed to the success of this project.

I am also deeply appreciative of **Olaf Stroosma**, **Olaf Grevenstuk**, **Ferdinand Postema**, **Harold Thung**, and **Andries Muis** for their invaluable support in integrating the simulator and installing the new overhead panel. Their teamwork and dedication were indispensable, particularly their last-minute work on soldering the wires in the yoke a day before a large planned evaluation campaign.

A special thanks to **Michiel de Galan** for his support, enthusiasm, and insightful feedback from a Human Factors and pilot's perspective, as well as for connecting me with many pilots. I'm grateful for the chance to collaborate and am glad our meetings could inspire your work on contingency management too. I truly enjoyed our meetings and visits to the operation center, which gave me the opportunity to gain insight into day-to-day flight operations. Something that I will always cherish.

I would also like to acknowledge **Erik-Jan Huijbrechts**, who provided feedback from the earliest stages of the project all the way through to the end. His insights and suggestions were invaluable in shaping the direction of this work at an early stage.

I extend my sincere gratitude to all the participants in the experiments for their time, valuable feedback, and professionalism. Their involvement was essential to the success of this work.

I am also incredibly grateful to my PhD colleagues and the Control and Simulation (C&S) staff: **Malik**, **Paolo**, **Yke**, **Kasper**, **Daniel**, **Mario**, **Wei**, **Matej**, **Sihao**, **Jerom**, **Jaime**, **Diana**, **Kimberly**, **Kirk**, **Ivan**, **Annemarie**, **Sven**, **Federico**, **Noor**, **Rowenna**, **Gijs**, **Yingfy**, **Menno**, **Hans**, **Alexander**, **Joost**, **Junzi**, **Daan**, **Erik-Jan**, **Coen**, and many others. Thank you for the countless engaging conversations over coffee, barbecues, sailing trips, tennis sessions, and drinks at the Atmosphere. Special thanks to **Rolf** for the time spent with MPS in the 737 and A320 simulators, and to **Bertine** for her administrative support, which made navigating the RINGO project much smoother. I genuinely believe that the talent and skills within this group are world-class.

I am deeply thankful to rely on my parents **Ben**, **Yta**, sister **Lizette**, and brother-in-law **Daniel** for their unending patience listening to my conversations on flight operations, displays, automation, coding — topics that will likely continue to come up, even though not always asked for. I owe special thanks to my father for sparking my passion for aviation by taking me to airbases and airshows across Europe and for our shared journey in obtaining a Private Pilot License.

Last but certainly not the least, my deepest thanks goes to **Naomi**, the love of my life, for her endless support and patience. You have been there every step of the way, always willing to listen to my sometimes perceived boring stories, no matter how often I repeated them. Thank you.

A

Level of Automation Taxonomy

Throughout the thesis, the automation taxonomy is used to categorize enhancements in automation. This taxonomy was introduced by Save & Feuerberg (2012). Additional background information and examples can be found in (Save & Feuerberg, 2012). Below a description is provided of the types and levels of automation. The information acquisition and information analysis stages consist both of 5 levels, whereas the decision selection and action implementation stages have 6 and 8 levels, respectively.

A INFORMATION ACQUISITION	B INFORMATION ANALYSIS	C DECISION AND ACTION SELECTION	D ACTION IMPLEMENTATION
A0 Manual Info Acquisition	B0 Working Memory Based Info Analysis	C0 Human Decision Making	D0 Manual Action and Control
The human acquires relevant information on the process s/he is following without using any tool.	The human compares, combines and analyses different information items regarding the status of the process s/he is following by way of mental elaborations.	The human generates decision options, selects the appropriate ones and decides all actions to be performed.	The human executes and controls all actions manually.
A1 Artefact-Supported Info Acquisition	B1 Artefact-Supported Info Analysis	C1 Artefact-Supported Decision Making	D1 Artefact-Supported Action Implementation
The human acquires relevant information on the process s/he is following with the support of low-tech non-digital artifacts.	The human compares, combines, and analyses different information items regarding the status of the process s/he is following utilizing paper or other non-digital artifacts.	The human generates decision options, selects the appropriate ones and decides all actions to be performed utilizing paper or other non-digital artifacts.	The human executes and controls actions with the help of mechanical non-software based tools.

A

A2 Low-Level Automation Support of Info Acquisition	B2 Low-Level Automation Support of Info Analysis	C2 Automated Decision Support	D2 Step-by-step Action Support
The system supports the human in acquiring information on the process s/he is following. Filtering and/or highlighting of the most relevant information are up to the human.	Based on user's request, the system helps the human in comparing, combining and analyzing different information items regarding the status of the process being followed.	The system proposes one or more decision alternatives to the human, leaving freedom to the human to generate alternative options. The human can select one of the alternatives proposed by the system or her/his own one.	The system assists the operator in performing actions by executing part of the action and/or by providing guidance for its execution. However, each action is executed based on human initiative and the human keeps full control of its execution.
A3 Medium-Level Automation Support of Info Acquisition	**B3 Medium-Level Automation Support of Info Analysis**	**C3 Rigid Automated Decision Support**	**D3 Low-Level Support of Action Sequence Execution**
The system supports the human in acquiring information on the process s/he is following. It helps the human in integrating data coming from different sources and in filtering and/or highlighting the most relevant information items, based on user's settings.	Based on user's request, the system helps the human in comparing, combining and analyzing different information items regarding the status of the process being followed. The system triggers visual and/or aural alerts if the analysis produces results requiring attention by the user.	The system proposes one or more decision alternatives to the human. The human can only select one of the alternatives or ask the system to generate new options.	The system performs automatically a sequence of actions after activation by the human. The human maintains full control of the sequence and can modify or interrupt the sequence during its execution.

A4 High-Level Automation Support of Info Acquisition	B4 High-Level Automation Support of Info Analysis	C4 Low-Level Automatic Decision Making	D4 High-Level Support of Action Sequence Execution
The system supports the human in acquiring information on the process s/he is following. The system integrates data coming from different sources and filters and/or highlights the information items which are considered relevant for the user. The criteria for integrating, filtering and highlighting the relevant information are predefined at design level but visible to the user.	The system helps the human in comparing, combining and analyzing different information items regarding the status of the process being followed, based on parameters pre-defined by the user. The system triggers visual and/or aural alerts if the analysis produces results requiring attention by the user.	The system generates options and decides autonomously on the actions to be performed. The human is informed of its decision.	The system performs automatically a sequence of actions after activation by the human. The human can monitor all the sequence and can interrupt it during its execution.
A5 Full Automation Support of Info Acquisition	B5 Full Automation Support of Info Analysis	C5 High-Level Automatic Decision Making	D5 Low-Level Automation of Action Sequence Execution
The system integrates data coming from different sources and filters and/or highlights the information items considered relevant for the user.	The system performs comparisons and analyses of data available on the status of the process being followed based on parameters defined at design level. The system triggers visual and/or aural alerts if the analysis produces results requiring attention by the user.	The system generates options and decides autonomously on the action to be performed. The human is informed of its decision only on request. (Always connected to to an Action Implementation level not lower than D5.)	The system initiates and executes automatically a sequence of actions. The human can monitor all the sequence and can modify or interrupt it during its execution.
		C6 Full Automatic Decision Making	D6 Medium-Level Automation of Action Sequence Execution
		The system generates options and decides autonomously on the action to be performed without informing the human. (Always connected to an Action Implementation level not lower than D5.)	The system initiates and executes automatically a sequence of actions. The human can monitor all the sequence and can interrupt it during its execution.

A

			D7 High-Level Automation of Action Sequence Execution
			The system initiates and executes a sequence of actions. The human can only monitor part of it and has limited opportunities to interrupt it.
			D8 Full Automation of Action Sequence Execution
			The system initiates and executes a sequence of actions. The human cannot monitor nor interrupt it until the sequence is not terminated.

References

Save, L. & Feuerberg, B. (2012). Designing Human-Automation Interaction: a new level of Automation Taxonomy. (pp. 978–0).

B

Functional Messages Presented on Functional System Status Display

One of the design display elements introduced in Chapter 5 was the Functional System Status Display (FSSD), but did not receive as much attention as the other display elements. Some pilots liked the overview instead of the EICAS messages and some found it a bit confusing since another syntax is used.

The FSSD consist out of two main view ports, which are 1) the impacts introduced by the system on the flight plan, presented on the upper part of the display and 2) the system states presented on a functional level (i.e., the aircraft capability), presented on the lower part of the display. Wording is deviating from the common functional description to make it more understandable for pilots (e.g., air instead of pneumatic).

The FSSD presents all the impacts and states in an alphanumerical form. A preliminary set of messages which are potentially presented on the upper part of the display are presented in Table B.1.

Table B.1: The messages that present the impact of the system on the operation.

System Impacts on Path
LAND AT NEAREST SUITABLE AIRPORT
No suitable alternate runways within range
1 suitable alternate runway within range
2 suitable alternate runways within range
No suitable alternate runways within range after G/A at XXXX
1 suitable alternate runway within range after G/A at XXXX
2 suitable alternate runways within range after G/A at XXXX
Landing distance at XXXX RWY ## ####m
NO LANDING AT XXXX
NO TAKEOFF XXXX
Maximum Crosswind ##kts

Rate of Climb Reduced to ####ft/min
Range Reduced to ####nm
Ceiling Reduced to ##,###ft
Asymmetric Thrust
Roll Rate Reduced
Go Around Performance Reduced
Increased fuel consumption +#.## kg/hr
VREF40 N/A
VREF30 N/A
VREF20 N/A
Airspeed limited to ###kts below ##,###ft
Airspeed limited to ###kts /0.##M
Separation by ATC
Self-Separation from Traffic
FLY MANUAL
Be cautious in proximity to terrain

System Impacts on Space

RVSM N/A
Class A N/A
Class B N/A
Class C N/A
Class D N/A
Class E N/A
Class F N/A
Avoid Icing Conditions
Avoid Turbulence

System Impacts on System and Passenger Health

OVERSPEED
FIRE ENG L
FIRE ENG R
FIRE APU
FIRE WHEEL WELL
FIRE CARGO
Airplane and/or cargo may have been damaged by fire
Fire in CARGO FWD may reignite
Flight above FL 250 not recommended
FLT DK Pressure Alt Excessive
CABIN ENV UNSAFE[1]
CABIN ENV UNSAFE in ## min
DUAL ENG FAIL
DUAL ENG FAIL in ## min

[1]Can be cabin alt, pressure, temperature, smoke, fumes, fire

ENG L FAIL in ## min
ENG R FAIL in ## min
ENG L flameout may occur
ENG R flameout may occur
NO FUEL in ## min
PILOT UNRESPONSIVE
MEDICAL EMERGENCY
Passenger comfort may be affected

Table B.2 lists all the functional state messages, or capabilities of the aircraft and crew. This list of messages is derived from the functional nodes identified in the ACWA (See Chapter 4). Please refer to Chapter 5 where the color coding, word choice and presentation is explained.

This list is based on Boeing 737-800 systems. Other planes have different levels of redundancies, or other systems. Furthermore, this list of capabilities is a preliminary version. It could be improved in terms of wording and completeness.

Table B.2: The system functionalities grouped by main function.

AutoFlight (AUTO FLT)
NO AUTOPILOT
AUTOPILOT B ONLY
AUTOPILOT A ONLY
NO AUTOLAND
NO AUTOTHROTTLE
AT 1 ONLY
AT 2 ONLY

Ground Controls (GND CTL)
NO ENG REV
ENG REV L ONLY
ENG REV R ONLY
ENG REV L SLOW
ENG REV R SLOW
NO ANTI-SKID
NO AUTO SPEEDBRAKES
GROUND SPOILERS A ONLY
GROUND SPOILERS B ONLY
NO GROUND SPOILERS
NO NWS
NWS ALTN ONLY
NO GEAR EXTENSION
MANUAL GEAR EXTENSION ONLY
MAIN GEAR R TIRES DEGRADED
MAIN GEAR L TIRES DEGRADED

NW TIRE DEGRADED
NO AUTOBRAKE
AUTOBRAKE RTO ONLY
AUTOBRAKE 1 ONLY
AUTOBRAKE 2 ONLY
AUTOBRAKE 3 ONLY
BRAKES ALTN ONLY
BRAKES ACCU ONLY
NO BRAKES

Flight Controls (FLT CTL)

NO GEAR RETRACTION
NO FLAPS 40
NO FLAPS 30
NO FLAPS 15
NO FLAPS 10
NO FLAPS 5
NO FLAPS 2
NO FLAPS 1
NO FLAPS
NO LE FLAP EXTND
NO LE FLAP RETRCT
LE FLAP EXTND ALTN ONLY
LE FLAP RETRCT ALTN ONLY
NO TE FLAP EXTND
NO TE FLAP RETRCT
TE FLAP EXTND ALTN ONLY
TE FLAP RETRCT ALTN ONLY
FLT SPLRS A ONLY
FLT SPLRS B ONLY
NO FLT SPOILERS
AILERON HYD A ONLY
AILERON HYD B ONLY
AILERON MANUAL ONLY
ELEV FEEL A ONLY
ELEV FEEL B ONLY
NO ELEV FEEL
ELEV HYD A ONLY
ELEV HYD B ONLY
ELEV MANUAL ONLY
RUD HYD A ONLY
RUD HYD B ONLY
RUD HYD STBY ONLY
NO RUDDER

NO YAW DAMPER
NO MACH TRIM
NO SPEED TRIM
NO AUTOSLAT
NO FLAP EXTENSION PROTECTIONS
FUEL IMBALANCE
ASYMMETRIC THRUST

Navigation / Position Precision (NAV)

RNAV 10 ONLY
NO RNAV 5
NO RNP 2
NO RNP 1
NO RNP 0.3
NO RNAV
ATC FIXES / RADAR N/A
UNRELIABLE ALTITUDE
UNRELIABLE AIRSPEED
RA R ONLY
RA L ONLY
UNRELIABLE TAS [if icing]
NO ILS LOC
NO ILS CAT I
NO ILS CAT II
NO ILS CAT III
NO GLS
NO RNP LPV
NO RNP LNAV/VNAV
NO RNP LNAV
NO RNAV (RNP) AR apch
NO VOR APP
VHF-NAV 1 OUT OF RANGE
VHF-NAV 2 OUT OF RANGE
AOA F/O ONLY
AOA CAPT ONLY
NO AOA

Communication (COM)

NO 2 WAY COM
VHF-1 NO SIGNAL
VHF-2 NO SIGNAL
HF-1 NO SIGNAL
HF-2 NO SIGNAL
VHF-1 ONLY

B

VHF-2 ONLY
HF-1 ONLY
HF-2 ONLY
SELCAL NO COVERAGE
NO SELCAL
NO FLT INTER PHONE
NO SERVICE/CAB INTER PHONE
NO PA SYSTEM
NO VHF DATA
NO VHF VOICE
NO HF VOICE
NO HF DATA
NO SAT VOICE
NO SAT DATA
XPNDR 1 ALT RPTG ONLY
XPNDR 2 ALT RPTG ONLY
XPNDR 1 ONLY
XPNDR 2 ONLY
NO XPNDR

Surveillance (SURV)

NO TCAS
NO TCAS TA/RA
NO GPWS
NO WX RADAR
OUTSIDE VIS CAPT ONLY
OUTSIDE VIS F/O ONLY
NO OUTSIDE VIS

Crew

##HRS ##MIN Duty Time Left
Licenses insufficient for intended operation

Anti-ice (AI)

ANTI-ICE WING L ONLY
ANTI-ICE WING R ONLY
NO ANTI-ICE WINGS
NO ANTI-ICE ENG L
NO ANTI-ICE ENG R
NO ANTI-ICE BOTH ENG
NO WINDOW HEAT FWD CPT
NO WINDOW HEAT FWD F/O
NO ANTI-ICE PROT PROBES

Cabin Environment (CAB ENV)

CABIN DEPRESS MANUAL ONLY
NO CABIN PRESS CTRL
NO CABIN TEMP CTRL
CABIN HEATING ONLY
CABIN COOLING ONLY
CREW OXYGEN in XX min depleted
CREW OXYGEN depleted
PAX OXYGEN in XX min depleted
PAX OXYGEN depleted
CABIN TEMP UNCONTROLLABLE
NO CABIN AIRFLOW
NO SEALED CABIN
FLT DK DOOR UNLKD
NO EQUIP COOL SUPPLY
NO EQUIP COOL EXHAUST
EQUIP COOL SUPPLY ALTN ONLY
EQUIP COOL EXHAUST ALTN ONLY
NO CARGO FWD DET
NO CARGO FWD FIRE EXT
NO CARGO AFT DET
NO CARGO AFT FIRE EXT

Passengers (PAX)

NO IFE / CABIN UTIL
BELTS FASTENED

Fuel Supply (FUEL)

CENTER depleted in XX min
CENTER depleted
MAIN L depleted in XX min
MAIN L depleted
MAIN R depleted in XX min
MAIN R depleted
FUEL TANKS depleted
FUEL LOW TEMP

Hydraulic Power (HYD)

HYD A ONLY
HYD B ONLY
HYD STBY ONLY
HYD A depleted in XX min
HYD A depleted

HYD B depleted in XX min
HYD B depleted
HYD STBY depleted in XX min
HYD STBY depleted

Electric Power (ELEC)

AC GEN 1 ONLY
AC GEN 2 ONLY
AC GEN APU ONLY
NO AC GEN
AC ON BAT
BAT depleted in XX min
DC TR1 ONLY
DC TR2 ONLY
DC TR3 ONLY
DC BAT ONLY
DC ON BAT ONLY
NO DC

Pneumatic Power (AIR)

BLEED ENG 1 ONLY
BLEED ENG 2 ONLY
BLEED APU ONLY
NO APU BLEED
L PACK ONLY
R PACK ONLY
NO PACKS

Mechanical Power (ENG)

LIMIT ENG 1 THRUST ##% N1
ENG 1 SUCTION FEED ONLY
NO ENG 1 FUEL SUPPLY
NO ENG 1 LIMIT PROT
ENG 1 FIRE DET A ONLY
ENG 1 FIRE DET B ONLY
NO ENG 1 FIRE DET
ENG 1 FIRE BOTTLE L ONLY
ENG 1 FIRE BOTTLE R ONLY
NO ENG 1 FIRE PROT
NO ENG 1 ICE PROT
NO ENG 1 START
NO ENG 1 IN-FLT START
NO ENG 1 LUBRICATION
ENG 2 ONLY

LIMIT ENG 2 THRUST ##% N1
ENG 2 SUCTION FEED ONLY
NO ENG 2 FUEL SUPPLY
NO ENG 2 LIMIT PROT
ENG 2 FIRE DET A ONLY
ENG 2 FIRE DET B ONLY
NO ENG 2 FIRE DET
ENG 2 FIRE BOTTLE L ONLY
ENG 2 FIRE BOTTLE R ONLY
NO ENG 2 FIRE PROT
NO ENG 2 START
NO ENG 2 START
NO ENG 2 IN-FLT START
NO ENG 2 LUBRICATION
ENG 1 ONLY

NO APU FUEL SUPPLY
APU FIRE DET A ONLY
APU FIRE DET B ONLY
NO APU FIRE DET
APU FIRE BOTTLE L ONLY
APU FIRE BOTTLE R ONLY
NO APU FIRE PROT
NO APU

C

Flight Plan, Airport and Performance Documentation

The experiment as presented in Chapter 6 was conducted in a 'fake' operating world to avoid any mix-ins with past experiences. The pilots were shortly briefed on each of the airports an provided with the flight plan and documentation presented in this appendix. The tables used to calculate the landing distance are also presented here. This documentation is edited and is therefore only usable for research and use in a simulator. In other words, do not use this information for any flight operation.

```
[ OFP ]
---------------------------------------------------------------------
DU0961     18FEB2020    IWLL-IRDM    B738 PHSIM    RELEASE 1046 18FEB20
OFP 1  ORVILL WRIGHT INTERCON-REDMOUNTAIN INTL
                         WX PROG 1812 1815 1818   OBS 1112 1112 1112

  ATC C/S    DU961           IWLL/WLL    IRDM/RDM      CRZ SYS      CI 80
18FEB2020    PHSIM           1210/1230   1626/1634     GND DIST      1432
B737-800 / CFM56-7B26                    STA   1610    AIR DIST      1692
                             CTOT:....                 G/C DIST      1338
                                                       AVG WIND   285/079
MAXIMUM    TOW  79016  LAW  66361  ZFW  62732          AVG W/C       M066
ESTIMATED  TOW  75346  LAW  64486  ZFW  60878          AVG ISA       M002
                                                       AVG FF KGS/HR 2759
                                                       FUEL BIAS    P00.0
ALTN IOPK                                              TKOF ALTN  .......
FL STEPS IWLL/0320/LAA/0340
--------------------------------------------------------------------
-DISP RMKS   APU N/A

---------------------------------------------------------------------
         PLANNED FUEL
---------------------------------
FUEL            ARPT   FUEL   TIME
---------------------------------
TRIP             RDM  10860   0356
CONT 15 MIN             690   0015
ALTN             OPK   1895   0047
FINRES                 1023   0030
---------------------------------
MINIMUM T/OFF FUEL    14468   0528
---------------------------------
EXTRA                     0   0000
---------------------------------
T/OFF FUEL            14468   0528
TAXI             WLL    227   0020
---------------------------------
BLOCK FUEL       WLL  14695
PIC EXTRA             ...0.
TOTAL FUEL            14695.
REASON FOR PIC EXTRA .....none....
---------------------------------------------------------------------
NO TANKERING RECOMMENDED (P)
---------------------------------------------------------------------
I HEREWITH CONFIRM THAT I HAVE PERFORMED A THOROUGH SELF BRIEFING
ABOUT THE DESTINATION AND ALTERNATE AIRPORTS OF THIS FLIGHT
INCLUDING THE APPLICABLE INSTRUMENT APPROACH PROCEDURES, AIRPORT
FACILITIES, NOTAMS AND ALL OTHER RELEVANT PARTICULAR INFORMATION.

DISPATCHER: EMMA AYALA                  PIC NAME: X

TEL: +1 800 555 0199               PIC SIGNATURE: ......X.......
```

DO NOT USE FOR FLIGHT

```
ALTERNATE ROUTE TO:                                            FINRES   1023
APT       TRK DST              VIA                        FL   WC   TIME   FUEL
--------------------------------------------------------------------
IOPK/26   287 179  DIDLY5 MLP J136 OPK DCT              320 M092 0047   1895
--------------------------------------------------------------------

MEL/CDL  ITEMS  DESCRIPTION
------------- -----------
```

APU N/A

```
--------------------------------------------------------------------

ROUTING:

ROUTE ID: DEFRTE
IWLL/33R LOA3 FUZ J58 SPS J168 LAA J20 FQF J56 RIDJE DCT RIW DCT HIA
DCT JIROS DCT DIPHU DCT NEGOE DCT JELEG DCT IRDM/12

--------------------------------------------------------------------
                         OPERATIONAL IMPACTS
                         -------------------
WEIGHT CHANGE UP 1.0          TRIP  P 0091 KGS   TIME P 0000
WEIGHT CHANGE DN 1.0          TRIP  M 0124 KGS   TIME P 0001
FL CHANGE     UP FL1                 NOT AVAILABLE
FL CHANGE     DN FL1          TRIP  P 0190 KGS   TIME M 0001
FL CHANGE     DN FL2          TRIP  P 0574 KGS   TIME M 0006
SPD CHANGE    CI 0            TRIP  M 0372 KGS   TIME P 0015
SPD CHANGE    CI 100          TRIP  P 0038 KGS   TIME M 0000
--------------------------------------------------------------------
                               WEIGHTS
                               -------
```

	EST	MAX	ACTUAL	
PAX	184		..181..	
CARGO	0.2		..0.6.	
PAYLOAD	19.2		.19.2..	
ZFW	60.9	62.7	.60.9.	
FUEL	14.7	16.6	..14.7.	POSS EXTRA 1.9
TOW	75.3	77.2	LDG..75.3.	
LAW	64.5	65.3	......	

FLIGHT LOG

MOST CRITICAL MORA 16100 FEET AT TOMSN///MXSHR 05 AT HGO

AWY POSITION IDENT FREQ	LAT LONG	EET TTLT	ETO ATO	FL MORA DIS	IMT ITT RDIS	MN TAS GS	WIND COMP SHR	OAT TDV TRP	EFOB AFOB	PBRN ABRN
					331				14.5	0.2
ORWILL WRIG	N2959.1		...	24	334		P009			
IWLL	W09520.5	0000	...		1432	404			14.5	0.2
LOA3				212	333	.63	228/039	M22	13.9	0.8
WLLIS	N3032.1	0006	...	25	335		P009	P05		
WLLIS	W09539.1	0006	...	37	1395	404		337	13.9	0.8
LOA3				285	339	.75	239/054	M37	13.2	1.5
LEONA	N3107.4	0007	...	26	341		P002	P05		
LOA	W09558.1	0013	...	39	1356	452		337	13.1	1.6
110.80										
WARMHILL FIR/UIR										
-IWLL	N3125.7		...							
	W09605.1		...	20	1336					
LOA3				320	339	.78	247/074	M46	12.6	2.1
T O C	N3142.5	0004	...	25	341	458	M001	P03		
	W09611.7	0020	...	17	1319	457	4	340	12.6	2.2
LOA3				320	314	.80	247/074	M46	12.5	2.2
DOLEY	N3211.4	0003	...	29	316	471	M001	P03		
DOLEY	W09623.1	0023	...	30	1289	470	4	340	12.5	2.2
LOA3				320	310	.80	243/085	M47	12.1	2.6
RANGER	N3253.4	0008	...	32	313	471	M032	P02		
FUZ	W09710.8	0031	...	58	1231	439	3	339	12.1	2.6
115.70										
J58				320	309	.80	240/088	M47	11.8	2.9
BATIK	N3326.9	0007	...	33	312	470	M033	P02		
BATIK	W09753.6	0038	...	49	1182	437	4	338	11.8	2.9
J58				320	319	.80	241/091	M48	11.4	3.3
PEAKS FAL	N3359.2	0007	...	64	323	470	M038	P01		
SPS	W09835.6	0045	...	48	1134	432	4	334	11.4	3.3
112.70										
J168				320	304	.80	251/071	M49	9.4	5.3
LAMAR	N3811.8	0006	...	78	310	468	M027	P00		
LAA	W10241.3	0128	...	50	813	441	4	330	9.4	5.2
116.90										
J20				340	311	.81	306/055	M58	9.0	5.7
HUGO	N3849.1	0009	...	89	318	461	M055	M05		
HGO	W10337.3	0137	...	58	755	406	5	338	9.1	5.7
112.10										
DRYSAND FIR/UIR										
-IDSD	N3899.7		...							
	W10375.4		...	02	753					

AWY POSITION IDENT FREQ	LAT LONG	EET TTLT	ETO ATO	FL MORA DIS	IMT ITT RDIS	MN TAS GS	WIND COMP SHR	OAT TDV TRP	EFOB AFOB	PBRN ABRN
J20 QUAIL QUAIL	W11405.4 N3915.6 W10407.5	0356 0005 0142	... ...	340 89 33	311 318 720	.81 461 407	306/055 M054 5	M58 M05 338	8.7 .... 8.7	6.0 .... 6.1
J20 FALCON FQF 116.30	N3941.4 W10437.3	0005 0147	... ...	340 129 35	309 317 685	.81 462 409	302/055 M053 5	M57 M04 346	8.5 .... 8.4	6.2 .... 6.3
J56 TOMSN TOMSN	N4021.4 W10526.2	0008 0155	... ...	340 161 55	308 316 630	.81 462 409	302/055 M053 5	M57 M04 346	8.1 .... 7.9	6.6 .... 6.8
J56 RIDJE RIDJE	N4031.1 W10538.3	0002 0157	... ...	340 153 33	313 321 617	.81 461 376	312/085 M085 3	M58 M05 341	8.0 .... 7.9	6.7 .... 6.8
DCT RIVERTON RIW 108.80	N4303.9 W10827.3	0013 0230	... ...	340 153 76	308 317 419	.81 462 363	308/101 M099 3	M58 M05 343	6.6	8.1 ....
DRYSTONE FIR/UIR -IDST	N4417.9 W10375.5		... ...	91	328					
GRANDWALL FIR/UIR -IRDM	N4550.6 W11169.2		... ...	108	220					
DCT WHITEHALL HIA 113.70	N4551.7 W11210.2	0042 0312	... ...	340 117 32	287 299 188	.81 463 330	307/134 M133 5	M57 M04 341	4.8	9.9 ....
DCT T O D	N4636.0 W11406.7	0018 0330	... ...	340 117 92	285 298 96	.81 463 313	305/151 M150 5	M57 M04 336	4.0	10.7 ....
DCT JIROS JIROS	N4648.2 W11440.3	0006 0336	... ...	219 96 26	342 354 70	.64 280	300/113 M113	M32 M03 340	3.9	10.8 ....

DU 961/18 FEB/WLL-RDM

Page 5

AWY				FL	IMT	MN	WIND	OAT	EFOB	PBRN
POSITION	LAT	EET	ETO	MORA	ITT	TAS	COMP	TDV		
IDENT	LONG	TTLT	ATO	DIS	RDIS	GS	SHR	TRP	AFOB	ABRN
FREQ										
DCT				182	009	.60	299/089	M28	3.9	10.8
DIPHU	N4656.6	0002	...	99	022		M058	M07		
DIPHU	W11441.4	0338	...	8	62	309		340	....	....
DCT				112	117	.52	292/032	M24	3.9	10.8
NEGOE	N4710.8	0003	...	100	130		M002	M17		
NEGOE	W11432.8	0341	...	15	47	319		340	....	....
DCT				079	117	.43	279/014	M19	3.9	10.8
JELEG	N4705.9	0002	...	96	130		P012	M18		
JELEG	W11424.3	0343	...	7	40	284		336	....	....
DCT									3.6	11.1
REDMOUNT IN	N4655.0	0013	...							
IRDM	W11405.4	0356	...	40					....	....

```
---------------------------------------------------------------------
                         WIND INFORMATION
                         ----------------

CLIMB             T O C             DOLEY             FUZ
350 250/080 -48   360 250/088 -48   360 250/088 -48   360 247/096 -49
310 245/064 -43   340 249/082 -50   340 249/082 -50   340 245/091 -51
200 236/039 -19   320 247/074 -46   320 247/074 -46   320 243/085 -47
150 232/030 -05   300 244/067 -43   300 244/067 -43   300 241/080 -43
100 237/026 +02   280 239/061 -37   280 239/061 -37   280 237/074 -38

BATIK             SPS               LAA               HGO
360 245/099 -49   360 244/104 -49   360 270/059 -53   380 282/067 -51
340 243/095 -51   340 242/098 -51   340 276/054 -54   360 293/060 -55
320 240/088 -47   320 241/091 -48   320 280/047 -51   340 306/055 -58
300 237/081 -43   300 240/084 -45   300 286/041 -49   320 310/053 -54
280 237/077 -38   280 238/078 -40   280 279/043 -44   300 314/051 -50

QUAIL             FQF               TOMSN             RIDJE
380 282/067 -51   380 281/063 -57   380 281/063 -57   380 296/069 -56
360 293/060 -55   360 291/058 -57   360 291/058 -57   360 305/076 -57
340 306/055 -58   340 302/055 -57   340 302/055 -57   340 312/085 -58
320 310/053 -54   320 310/059 -53   320 310/059 -53   320 311/084 -54
300 314/051 -50   300 317/063 -50   300 317/063 -50   300 309/083 -49

RIW               HIA               T O D             DESCENT
380 300/084 -57   380 304/102 -55   380 304/106 -54   350 305/140 -56
360 305/099 -58   360 306/123 -55   360 305/129 -55   310 305/150 -50
340 308/115 -58   340 307/144 -56   340 305/151 -57   200 298/097 -32
320 306/110 -54   320 307/144 -53   320 305/150 -52   150 298/055 -29
300 305/105 -50   300 306/143 -49   300 305/149 -48   100 288/027 -24

---------------------------------------------------------------------
```

[Airport WX List]

```
-------------------------------------------------------------------
IWLL --> IRDM    DU   961 / 18FEB2020
LIDO/WEATHER SERVICE       DATE : 18Feb2020   TIME : 10:46 UTC

AIRMETs:
  No Wx data available

SIGMETs:
IRDM  GRANDWALL FIR/UIR
  WS  SIGMET UNIFORM 1 VALID 1810/1903 IRDM
             IRDM GRANDWALL FIR ICE FCST AT 01230Z FROM SURFACE
             AND FL300 CONDS ENDG 1930Z.
```

Departure:

```
IWLL/WLL  ORWILL WRIGHT INTERCONTINENTAL/H
  SA  180953  34010KT 8000 OVC032 12/08 Q1019

  FT  180930  1810/1912 34010G17KT 9999 OVC040
```

Destination:

```
IRDM/RDM  REDMOUNTAIN INTL
  SA  180953  AUTO 13003KT 7000 OVC038 M05/M08 Q1026

  FT  180520  1806/1906 14003KT 9999 OVC045
```

Destination Alternates:

```
IOPK/OPK  OATPEAKS INTL
  SA  180953  AUTO 23021KT 9999 SCT060 BKN200 M05/M12 Q1027

  FT  180526  1806/1906 24025KT 9999 FEW060 SCT200
              FM181300 25022KT 9999 BKN065
              FM181600 27025KT 9999 BKN120 OVC150
              FM190300 26522KT 7000 -SN BKN060 OVC032

IDST/DST  DRYSTONE INTL
  SA  180953  15003KT 9999 SCT060 BKN180 03/M02 Q1027

  FT  180526  1806/1906 15004KT 9999 FEW060 SCT200


IWLF/WLF  WILLOWFORT RGNL
  SA  180953  14010KT 9999 SCT080 BKN200 02/M05 Q1027

  FT  180526  1806/1906 14012KT 9999 FEW080 SCT200

  AIRPORTLIST ENDED
```

[NOTAM]

===================================
DESTINATION AIRPORT - DETAILED INFO
===================================

IRDM/RDM REDMOUNTAIN

++++++++++++++++++++++++++++++ AIRPORT ++++++++++++++++++++++++++++++

A1259/21
APN ALL PATCHY ICE AND PATCHY COMPACTED SN OBS AT 2102180935.
A1258/21
TWY ALL PATCHY ICE OBS AT 2102180930.
A1237/21
TWY ALL PATCHY COMPACTED SN AND WET OBS AT 2102171942.
A0068/21
TWY A5 CLSD
A0067/21
TWY A2 CLSD
A2986/20
TWY G BTN **RWY 12/30** AND APCH END **RWY 08 CLSD**

++++++++++++++++++++++++++++++ RUNWAY ++++++++++++++++++++++++++++++

A1257/21
RWY 12 10 PCT ICE OBS AT 2102180927 BA MEDIUM.
A2486/20
RWY 08/26 CLSD

================================
DESTINATION ALTERNATE AIRPORT(S)
================================

IOPK/OPK   OATPEAKS INTL

++++++++++++++++++++++++++++++ AIRPORT ++++++++++++++++++++++++++++++

A3724/21
APRON ALL PATCHY COMPACTED SN OBS AT 2102180049.
02/749   VALID: 17-FEB-21 1458 - 18-FEB-21 1458
APRON TERMINAL RAMP, WEST AIR CARGO RAMP FICON
PATCHY COMPACTED SN AND   PATCHY 1/8IN SLUSH OBS AT 2102171458.
A3635/21   VALID: 17-FEB-21 1050 - 18-FEB-21 1050
TWY A SOUTH HLDG PAD, G NORTH HLDG PAD, G SOUTH HLDG PAD, C1, C2, C4, D, H, K, **TWY C** BTN **TWY C1** AND **TWY G**, **TWY** C BTN **TWY C4** AND **TWY A** PATCHY COMPACTED SN AND 1/8IN DRY SN BA MEDIUM OBS AT 2102171050.
A3631/21   VALID: 17-FEB-21 1049 - 18-FEB-21 1049
TWY A, A NORTH HLDG PAD, A1, A2, A3, A4, A5, A6, G, G1, G2, G3, G5, G6, **TWY C** BTN **TWY G** AND **TWY A** WET DEICED LIQUID 50FT WID REMAINDER 1/8IN DRY SN OBS AT 2102171049.

IDST/DST DRYSTONE INTL

+++++++++++++++++++++++++++++ AIRPORT ++++++++++++++++++++++++++++++

A234/21

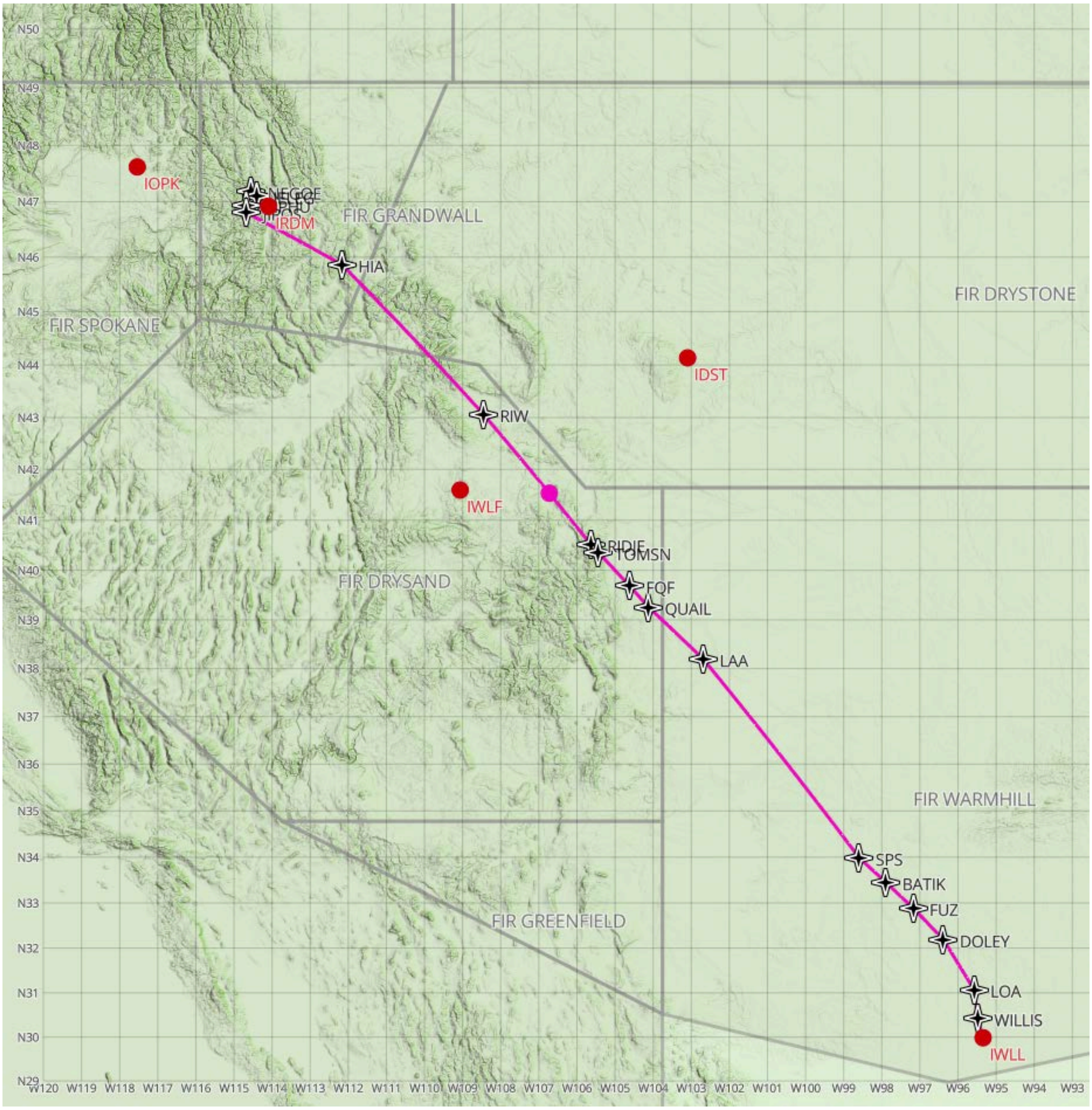
225´ CRANE 1 NM NORTHEAST OF ARPT.

IWLF/WLF WILLOWFORT RGNL

+++++++++++++++++++++++++++++ AIRPORT ++++++++++++++++++++++++++++++

A3724/21

PPR for air carrier ops with more than 30 pax seats, call arpt ops 307–352–6888. ARFF ICAO CAT 2 avbl with 30 min notice: call arpt ops 307–352–6888.



N50
N49
N48
N47
N46
N45
N44
N43
N42
N41
N40
N39
N38
N37
N36
N35
N34
N33
N32
N31
N30
N29
W120 W119 W118 W117 W116 W115 W114 W113 W112 W111 W110 W109 W108 W107 W106 W105 W104 W103 W102 W101 W100 W99 W98 W97 W96 W95 W94 W93
IOPK
NEGOE
IRDM
FIR GRANDWALL
HIA
FIR DRYSTONE
FIR SPOKANE
IDST
RIW
IWLF
TOMSN
FIR DRYSAND
FQF
QUAIL
LAA
FIR WARMHILL
SPS
BATIK
FUZ
FIR GREENFIELD
DOLEY
LOA
WILLIS
IWLL

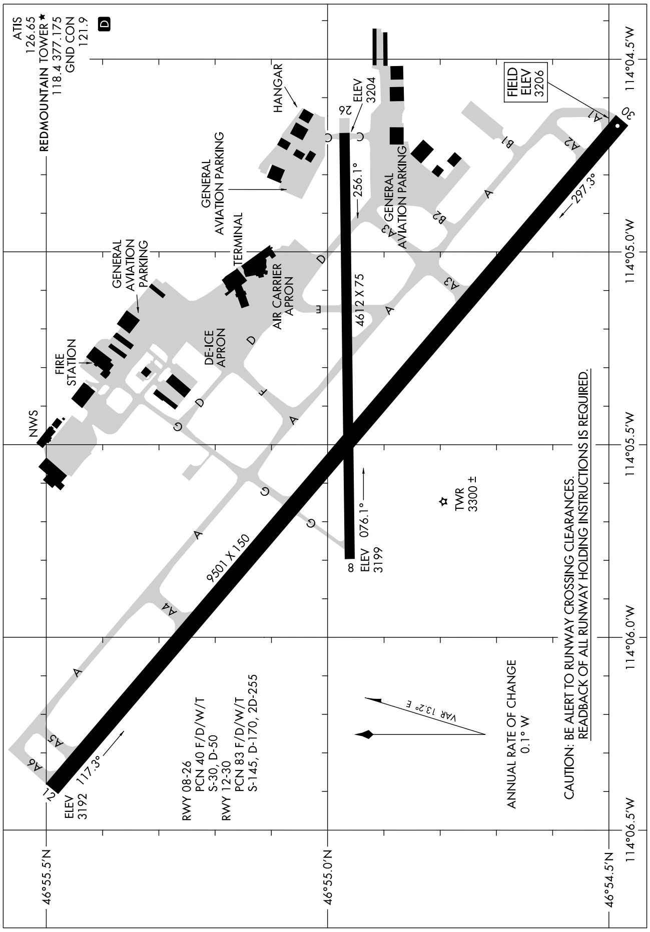
General Information:

ICAO/IATA: IRDM/RDM
Elevation: 3206 ft
Airport Use: Public
ARFF Index: C
Fuel Types: 100LL, JET A1+
Repair Types: Minor Airframe, Minor Engine
Customs: Yes

Airport Remarks:
Attended continuously. Parachute Jumping. Cold temperature airport. Altitude correction required at or below –12C. Migratory and small bird activity.

Approach Procedures:
ILS RWY 12
RNAV (RNP) Z RWY 12
RNAV (GPS) Y RWY 12
RNAV (GPS) RWY 30
VOR

Runway Info:
Runway 12-30 2896m x 45m
Runway 8-26 1406m x 22m



ATIS
126.65
REDMOUNTAIN TOWER ★
118.4 377.175
GND CON
121.9
D
HANGAR
GENERAL AVIATION PARKING
GENERAL AVIATION PARKING
TERMINAL
AIR CARRIER APRON
DE-ICE APRON
FIRE STATION
NWS
FIELD ELEV 3206
ELEV 3204
26
256.1°
4612 X 75
076.1°
8
ELEV 3199
30
297.3°
9501 X 150
117.3°
12
ELEV 3192
TWR 3300 ±
RWY 08-26
PCN 40 F/D/W/T
S-30, D-50
RWY 12-30
PCN 83 F/D/W/T
S-145, D-170, 2D-255
VAR 13.2° E
ANNUAL RATE OF CHANGE
0.1° W
CAUTION: BE ALERT TO RUNWAY CROSSING CLEARANCES.
READBACK OF ALL RUNWAY HOLDING INSTRUCTIONS IS REQUIRED.
A
A1
A2
A3
A4
A5
A6
B1
B2
C
D
E
F
G
114°04.5'W
114°05.0'W
114°05.5'W
114°06.0'W
114°06.5'W
46°55.5'N
46°55.0'N
46°54.5'N

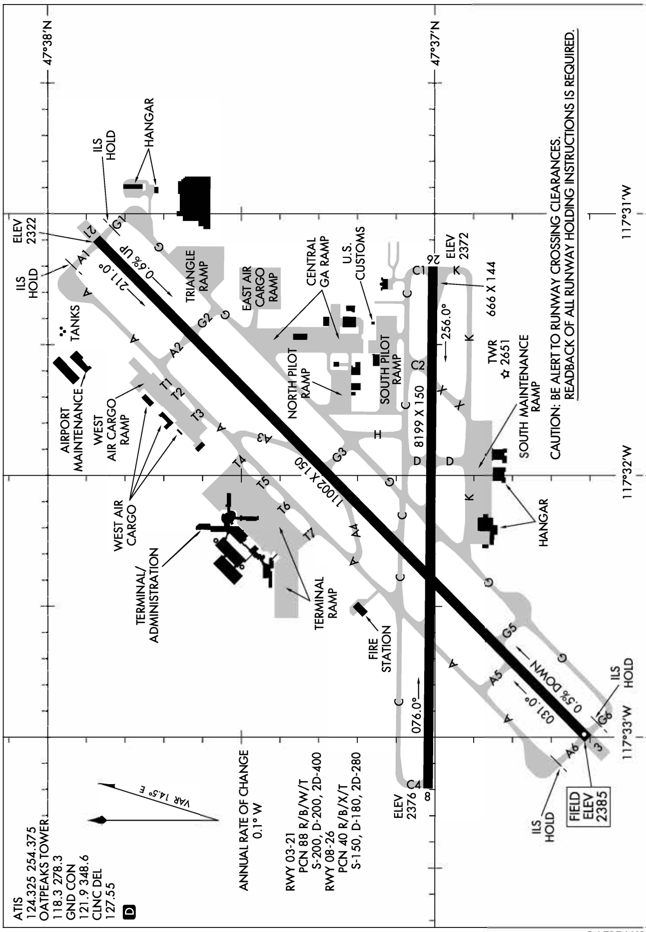
General Information:

ICAO/IATA: IOPK/OPK
Elevation: 2385 ft
Airport Use: Public
ARFF Index: C
Fuel Types: 100LL, JET A1+
Repair Types: Major Airframe, Major Engine
Customs: Yes

Airport Remarks:
Attended continuously. Waterfowl and birds on and invof arpt. Portions of Twy K not visible from twr.

Approach Procedures:
ILS or LOC RWY 3
ILS or LOC RWY 21
ILS RWY 3 (CAT II & CAT III)
ILS RWY 21 (CAT II & CAT III)
RNAV (RNP) Z RWY 3
RNAV (GPS) Y RWY 3
RNAV (GPS) RWY 21
RNAV (GPS) RWY 8
RNAV (GPS) RWY 26
VOR RWY 3

Runway Info:
Runway 3-21 3353m x 46m
Runway 8-26 2500m x 46m



47°38'N
47°37'N
117°31'W
117°32'W
117°33'W
ATIS
124.325 254.375
OATPEAKS TOWER
118.3 278.3
GND CON
121.9 348.6
CLNC DEL
127.55
VAR 14.5° E
ANNUAL RATE OF CHANGE
0.1° W
RWY 03-21
PCN 88 R/B/W/T
S-200, D-200, 2D-400
RWY 08-26
PCN 40 R/B/X/T
S-150, D-180, 2D-280
CAUTION: BE ALERT TO RUNWAY CROSSING CLEARANCES.
READBACK OF ALL RUNWAY HOLDING INSTRUCTIONS IS REQUIRED.
FIELD
ELEV
2385
ELEV
2322
ELEV
2372
ELEV
2376
11002 X 150
8199 X 150
666 X 144
0.6% UP
0.5% DOWN
211.0°
031.0°
256.0°
076.0°
ILS
HOLD
HANGAR
TANKS
AIRPORT
MAINTENANCE
WEST
AIR CARGO
RAMP
WEST AIR
CARGO
TERMINAL/
ADMINISTRATION
TERMINAL
RAMP
FIRE
STATION
TRIANGLE
RAMP
EAST AIR
CARGO
RAMP
CENTRAL
GA RAMP
U.S.
CUSTOMS
NORTH PILOT
RAMP
SOUTH PILOT
RAMP
TWR
2651
SOUTH MAINTENANCE
RAMP

General Information:

ICAO/IATA: IDST/DST
Elevation: 5344 ft
Airport Use: Public
ARFF Index: C
Fuel Types: 100LL, JET A1+
Repair Types: Major Airframe, Major Engine
Customs: Yes

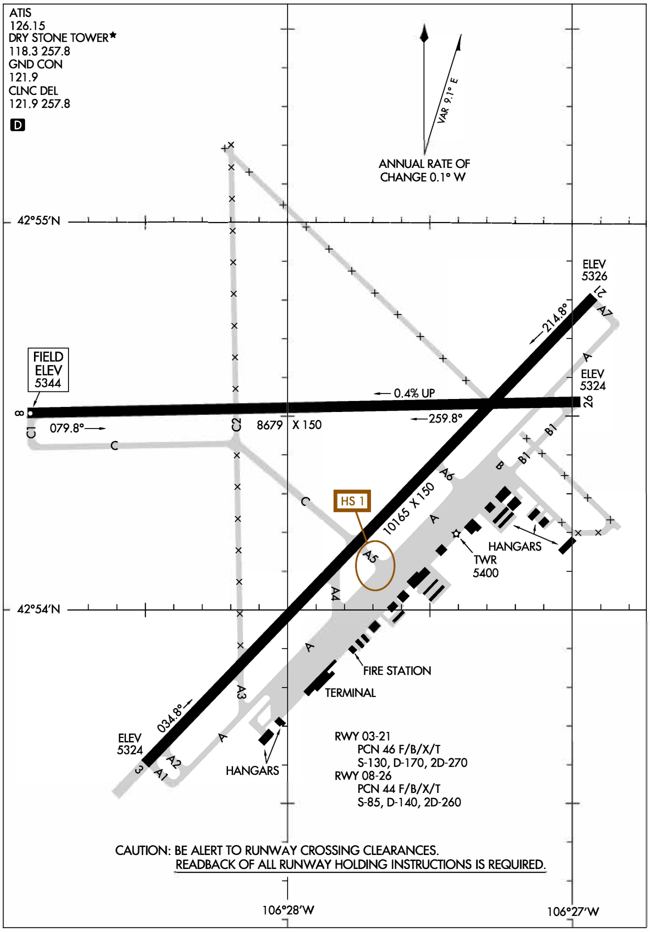
Airport Remarks:
Attended continuously. 225´ crane 1 NM northeast of arpt.

Approach Procedures:
ILS or LOC RWY 3
RNAV (GPS) RWY 3
RNAV (GPS) RWY 21
RNAV (GPS) RWY 8
RNAV (GPS) RWY 26
VOR/DME RWY 21

Runway Info:
Runway 3-21 3098m x 46m
Runway 8-26 2645m x 46m

AIRPORT DIAGRAM

DRYSTONE INTL (DST)
DRYSTONE



AIRPORT DIAGRAM

DRYSTONE
DRYSTONE INTL (DST)

General Information:

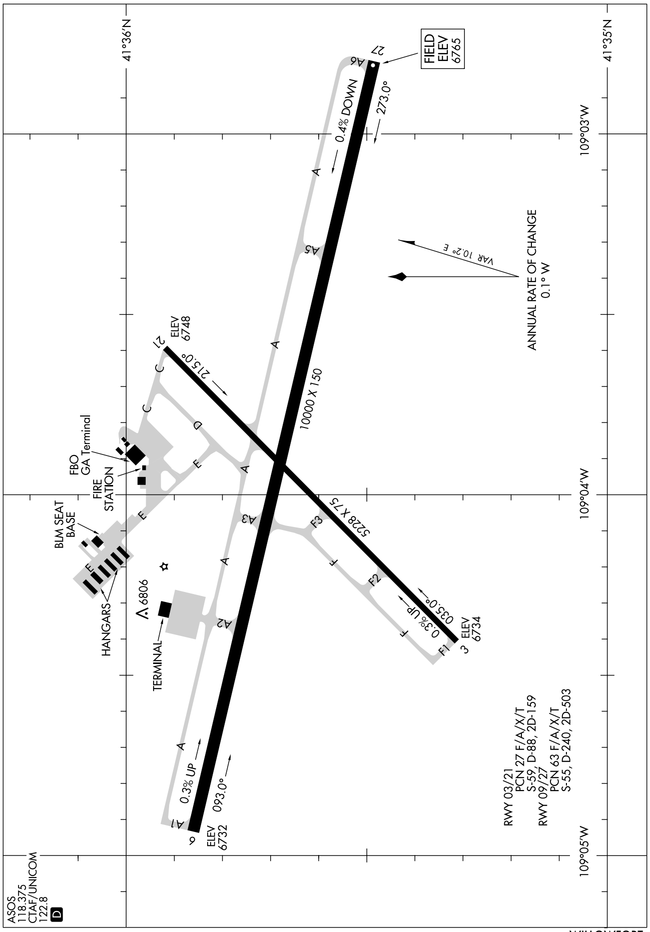
ICAO/IATA: IWLF/WLF
Elevation: 6765 ft
Airport Use: Public
ARFF Index—See Remarks
Fuel Types: 100LL, JET A1+
Repair Types: Minor Airframe, Minor Engine
Customs: Yes

Airport Remarks:
PPR for air carrier ops with more than 30 pax seats, call arpt ops 307-352-6888. ARFF ICAO Cat 2 avbl with 30 min notice: call arpt ops 307-352-6888.

Approach Procedures:
ILS or LOC RWY 27
RNAV (GPS) RWY 9
RNAV (GPS) RWY 27
VOR RWY 9

Runway Info:
Runway 9-27 3048m x 46m
Runway 3-21 1593m x 23m

AIRPORT DIAGRAM



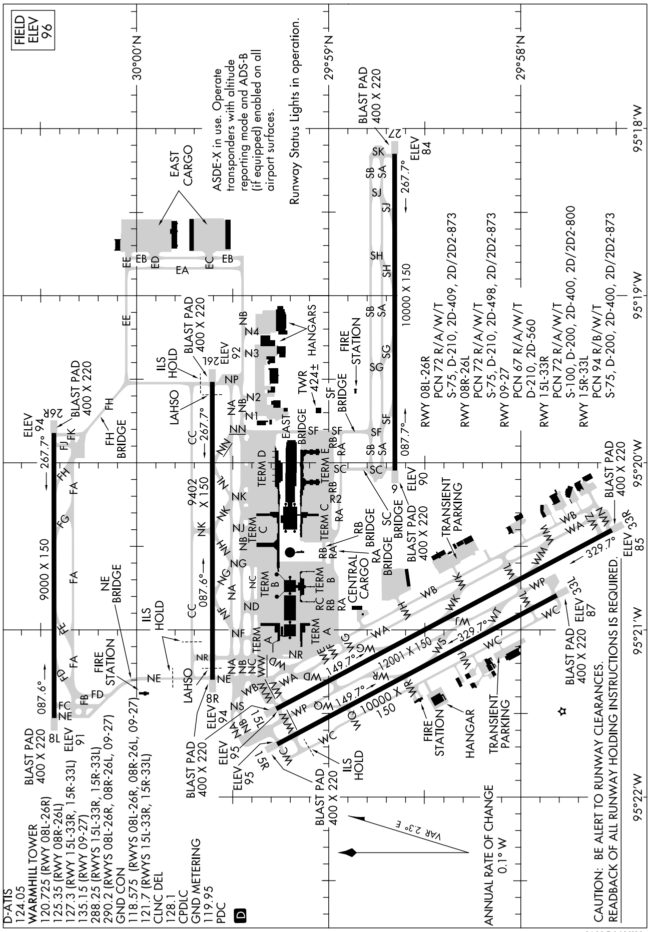
General Information:

ICAO/IATA: IWLL/WLL
Elevation: 96 ft
Airport Use: Public
ARFF Index: E
Fuel Types: 100LL, JET A1+
Repair Types: Major Airframe, Major Engine
Customs: Yes

Airport Remarks:
Attended continuously. Rwy 09–27 CLOSED to acft with wingspan 215´ and abv. Birds on and invof arpt.

Runway Info:
Runway 8L-26R 2743m x 46m
Runway 8R-26L 2866m x 46m
Runway 9-27 3048m x 46m
Runway 15L-33R 3658m x 46m
Runway 15R-33L 3048m x 46m

AIRPORT DIAGRAM



AIRPORT DIAGRAM

ADVISORY INFORMATION

Normal Configuration Landing Distances
Flaps 15

	LANDING DISTANCE AND ADJUSTMENT (M)											
	REF DIST	WT ADJ	ALT ADJ	WIND ADJ PER 10 KTS		SLOPE ADJ PER 1%		TEMP ADJ PER 10°C		APP SPD ADJ	REVERSE THRUST ADJ	
BRAKING CONFIGURATION	65000 KG LANDING WEIGHT	PER 5000 KG ABOVE/ BELOW 65000 KG	PER 1000 FT STD/HIGH*	HEAD WIND	TAIL WIND	DOWN HILL	UP HILL	ABV ISA	BLW ISA	PER 5 KTS ABOVE VREF15	ONE REV	NO REV
Dry Runway												
MAX MANUAL	975	75/-60	20/30	-35	120	10	-10	20	-20	35	20	40
MAX AUTO	1270	70/-70	30/40	-45	155	0	0	30	-30	60	0	5
AUTOBRAKE 3	1815	105/-115	50/65	-75	255	0	0	50	-50	100	0	0
AUTOBRAKE 2	2300	150/-160	70/95	-105	350	30	-45	70	-70	95	80	80
AUTOBRAKE 1	2530	180/-190	85/110	-120	410	70	-80	75	-75	90	220	335
Good Reported Braking Action												
MAX MANUAL	1330	75/-80	35/45	-60	200	30	-25	35	-35	45	65	145
MAX AUTO	1430	80/-85	40/50	-60	210	30	-25	35	-35	55	75	165
AUTOBRAKE 3	1820	105/-115	50/65	-75	260	5	-5	50	-50	100	5	10
AUTOBRAKE 2	2300	150/-160	70/95	-105	350	30	-45	70	-70	95	80	80
AUTOBRAKE 1	2530	180/-190	85/110	-120	410	70	-80	75	-75	90	220	335
Medium Reported Braking Action												
MAX MANUAL	1845	120/-120	60/75	-95	335	80	-65	50	-50	60	190	455
MAX AUTO	1885	125/-125	60/80	-95	340	75	-60	50	-55	70	190	460
AUTOBRAKE 3	2005	125/-130	60/80	-100	350	60	-40	55	-60	100	130	375
AUTOBRAKE 2	2350	155/-165	75/95	-115	395	65	-60	70	-70	95	115	230
AUTOBRAKE 1	2540	180/-190	85/110	-125	430	90	-85	75	-75	90	235	390
Poor Reported Braking Action												
MAX MANUAL	2430	175/-175	85/115	-140	535	205	-135	70	-75	75	415	1105
MAX AUTO	2430	175/-175	85/115	-140	535	205	-130	70	-75	80	415	1105
AUTOBRAKE 3	2460	175/-175	85/115	-145	535	195	-125	70	-75	90	420	1115
AUTOBRAKE 2	2625	185/-190	90/125	-150	555	190	-125	75	-80	95	350	960
AUTOBRAKE 1	2740	195/-200	95/130	-155	570	195	-140	80	-85	90	400	990

Reference distance is for sea level, standard day, no wind or slope, VREF15 approach speed and two engine detent reverse thrust.
For max manual braking and manual speed brakes, increase reference landing distance by 60 m.
For autobrake and manual speed brakes, increase reference landing distance by 50 m.
Actual (unfactored) distances are shown.
Includes distance from 50 ft above threshold (305 m of air distance).
***For landing distance at or below 8000 ft pressure altitude, apply the STD adjustment. For altitudes higher than 8000 ft, first apply the STD adjustment to derive a new reference landing distance for 8000 ft then apply the HIGH adjustment to this new reference distance.**

ADVISORY INFORMATION

Normal Configuration Landing Distances

Flaps 30

	LANDING DISTANCE AND ADJUSTMENT (M)											
	REF DIST	WT ADJ	ALT ADJ	WIND ADJ PER 10 KTS		SLOPE ADJ PER 1%		TEMP ADJ PER 10°C		APP SPD ADJ	REVERSE THRUST ADJ	
BRAKING CONFIGURATION	65000 KG LANDING WEIGHT	PER 5000 KG ABOVE/ BELOW 65000 KG	PER 1000 FT STD/HIGH*	HEAD WIND	TAIL WIND	DOWN HILL	UP HILL	ABV ISA	BLW ISA	PER 5 KTS ABOVE VREF30	ONE REV	NO REV
Dry Runway												
MAX MANUAL	935	60/-55	20/25	-35	120	10	-10	20	-20	35	15	35
MAX AUTO	1200	60/-65	25/35	-45	145	0	0	30	-30	55	0	5
AUTOBRAKE 3	1700	100/-105	45/60	-75	245	0	-5	45	-45	85	0	0
AUTOBRAKE 2	2120	140/-145	65/85	-100	335	30	-40	60	-60	85	80	80
AUTOBRAKE 1	2325	160/-170	75/100	-115	395	65	-70	70	-70	80	185	300
Good Reported Braking Action												
MAX MANUAL	1275	70/-75	35/45	-55	195	30	-25	30	-30	45	60	130
MAX AUTO	1375	75/-80	35/45	-60	205	30	-25	35	-35	55	65	145
AUTOBRAKE 3	1705	100/-105	45/60	-75	250	5	-10	45	-45	85	5	10
AUTOBRAKE 2	2120	140/-145	65/85	-100	335	30	-40	60	-60	85	80	80
AUTOBRAKE 1	2325	160/-170	75/100	-115	395	65	-70	70	-70	80	185	300
Medium Reported Braking Action												
MAX MANUAL	1740	110/-115	55/70	-90	325	80	-60	45	-50	60	165	390
MAX AUTO	1790	115/-120	55/75	-90	330	75	-60	50	-50	70	165	400
AUTOBRAKE 3	1885	115/-120	55/75	-95	340	55	-45	55	-55	85	115	330
AUTOBRAKE 2	2175	140/-150	65/90	-110	380	65	-60	65	-65	85	115	215
AUTOBRAKE 1	2340	160/-170	75/100	-120	410	90	-75	70	-70	80	195	350
Poor Reported Braking Action												
MAX MANUAL	2265	160/-160	75/105	-135	520	190	-125	65	-70	70	355	920
MAX AUTO	2275	160/-160	80/105	-135	520	190	-120	65	-70	80	350	920
AUTOBRAKE 3	2305	160/-160	80/105	-140	520	185	-120	65	-70	80	360	930
AUTOBRAKE 2	2435	170/-170	80/110	-145	535	180	-120	70	-75	85	315	810
AUTOBRAKE 1	2530	175/-180	85/115	-145	550	190	-130	75	-80	80	340	845

Reference distance is for sea level, standard day, no wind or slope, VREF30 approach speed and two engine detent reverse thrust.
For max manual braking and manual speed brakes, increase reference landing distance by 60 m.
For autobrake and manual speed brakes, increase reference landing distance by 50 m.
Actual (unfactored) distances are shown.
Includes distance from 50 ft above threshold (305 m of air distance).
***For landing distance at or below 8000 ft pressure altitude, apply the STD adjustment. For altitudes higher than 8000 ft, first apply the STD adjustment to derive a new reference landing distance for 8000 ft then apply the HIGH adjustment to this new reference distance.**

ADVISORY INFORMATION

Normal Configuration Landing Distances

Flaps 40

	LANDING DISTANCE AND ADJUSTMENT (M)											
	REF DIST	WT ADJ	ALT ADJ	WIND ADJ PER 10 KTS		SLOPE ADJ PER 1%		TEMP ADJ PER 10°C		APP SPD ADJ	REVERSE THRUST ADJ	
BRAKING CONFIGURATION	65000 KG LANDING WEIGHT	PER 5000 KG ABOVE/ BELOW 65000 KG	PER 1000 FT STD/HIGH*	HEAD WIND	TAIL WIND	DOWN HILL	UP HILL	ABV ISA	BLW ISA	PER 5 KTS ABOVE VREF40	ONE REV	NO REV
Dry Runway												
MAX MANUAL	890	50/-50	20/25	-35	115	10	-10	20	-20	35	15	30
MAX AUTO	1120	55/-60	25/30	-40	140	0	0	25	-25	55	0	0
AUTOBRAKE 3	1565	90/-100	40/55	-70	235	0	-5	40	-40	85	0	0
AUTOBRAKE 2	1980	125/-135	60/75	-95	325	25	-35	55	-55	90	40	40
AUTOBRAKE 1	2185	150/-155	70/90	-110	380	55	-65	65	-65	85	145	225
Good Reported Braking Action												
MAX MANUAL	1220	65/-70	30/40	-55	195	30	-25	30	-30	45	55	120
MAX AUTO	1310	70/-75	35/45	-60	200	25	-25	30	-30	55	60	130
AUTOBRAKE 3	1570	90/-100	40/55	-70	240	10	-5	40	-45	90	5	10
AUTOBRAKE 2	1980	125/-135	60/75	-95	325	25	-35	55	-55	90	40	40
AUTOBRAKE 1	2185	150/-155	70/90	-110	380	55	-65	65	-65	85	145	225
Medium Reported Braking Action												
MAX MANUAL	1660	105/-105	50/65	-90	320	75	-60	45	-45	60	150	350
MAX AUTO	1695	110/-110	50/70	-90	325	70	-55	45	-45	70	150	355
AUTOBRAKE 3	1760	110/-115	50/70	-90	330	60	-45	50	-50	85	115	325
AUTOBRAKE 2	2035	130/-140	60/80	-105	370	60	-55	60	-60	90	80	175
AUTOBRAKE 1	2195	150/-155	70/95	-115	400	80	-70	65	-65	85	160	275
Poor Reported Braking Action												
MAX MANUAL	2160	150/-150	70/100	-135	510	190	-120	60	-65	70	325	830
MAX AUTO	2165	150/-150	75/100	-135	510	190	-120	60	-65	75	325	830
AUTOBRAKE 3	2185	155/-155	75/100	-135	510	185	-120	60	-65	80	330	840
AUTOBRAKE 2	2300	160/-160	75/105	-140	525	175	-115	65	-70	85	275	730
AUTOBRAKE 1	2390	165/-170	80/110	-145	540	180	-125	70	-75	80	305	745

Reference distance is for sea level, standard day, no wind or slope, VREF40 approach speed and two engine detent reverse thrust.
For max manual braking and manual speed brakes, increase reference landing distance by 55 m.
For autobrake and manual speed brakes, increase reference landing distance by 45 m.
Actual (unfactored) distances are shown.
Includes distance from 50 ft above threshold (305 m of air distance).
***For landing distance at or below 8000 ft pressure altitude, apply the STD adjustment. For altitudes higher than 8000 ft, first apply the STD adjustment to derive a new reference landing distance for 8000 ft then apply the HIGH adjustment to this new reference distance.**

ADVISORY INFORMATION

Non-Normal Configuration Landing Distance

Dry Runway

LANDING CONFIGURATION	VREF	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 HEAD WIND	WIND ADJ PER 10 KTS TAIL WIND	SLOPE ADJ PER 1% DOWN HILL	SLOPE ADJ PER 1% UP HILL	APP SPD ADJ 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

Reference distance assumes sea level, standard day, with no wind or slope.
Actual (unfactored) distances are shown.
Includes distance from 50 ft above runway threshold (305 m of air distance).
Assumes maximum manual braking and maximum reverse thrust when available on operating engine(s).
Altitude adjustment for STD altitudes valid up to 8000 ft pressure altitude.
Altitude adjustment for HIGH altitudes valid for altitudes above 8000 ft up to 14000 ft.

***For landing distance above 8000 ft pressure altitude, first apply the STD altitude adjustment to derive new reference landing distance for 8000 ft, then apply applicable HIGH altitude adjustment between 8000 ft and 14000 ft to this new reference distance.**

****ONE ENGINE INOPERATIVE (FLAPS 30) data are only applicable to Fail Operational airplanes.**

ADVISORY INFORMATION

Non-Normal Configuration Landing Distance

Dry Runway

		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
STABILIZER TRIM INOPERATIVE	VREF15	910	70/-55	20/25	-30	115	10	-10	60
JAMMED OR RESTRICTED FLIGHT CONTROLS	VREF15	910	70/-55	20/25	-30	115	10	-10	60
TRAILING EDGE FLAP ASYMMETRY (30 ≤ FLAPS < 40)	VREF30	875	60/-50	20/25	-30	110	10	-10	60
TRAILING EDGE FLAP ASYMMETRY (15 ≤ FLAPS < 30)	VREF15	910	70/-55	20/25	-30	115	10	-10	60
TRAILING EDGE FLAP ASYMMETRY (1 ≤ FLAPS < 15)	VREF40+30	1015	85/-60	25/30	-35	120	10	-10	60
TRAILING EDGE FLAP DISAGREE (30 ≤ FLAPS < 40)	VREF30	875	60/-50	20/25	-30	110	10	-10	60
TRAILING EDGE FLAP DISAGREE (15 ≤ FLAPS < 30)	VREF15	910	70/-55	20/25	-30	115	10	-10	60
TRAILING EDGE FLAP DISAGREE (1 ≤ FLAPS < 15)	VREF40+30	1015	85/-60	25/30	-35	120	10	-10	60
TRAILING EDGE FLAPS UP	VREF40+40	1085	105/-65	25/30	-35	125	10	-10	65

Reference distance assumes sea level, standard day, with no wind or slope.
Actual (unfactored) distances are shown.
Includes distance from 50 ft above runway threshold (305 m of air distance).
Assumes maximum manual braking and maximum reverse thrust when available on operating engine(s).
Altitude adjustment for STD altitudes valid up to 8000 ft pressure altitude.
Altitude adjustment for HIGH altitudes valid for altitudes above 8000 ft up to 14000 ft.

***For landing distance above 8000 ft pressure altitude, first apply the STD altitude adjustment to derive new reference landing distance for 8000 ft, then apply applicable HIGH altitude adjustment between 8000 ft and 14000 ft to this new reference distance.**

ADVISORY INFORMATION

Non-Normal Configuration Landing Distance

Good Reported Braking Action

		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	1615	85/-90	45/60	-60	215	30	-30	85
ANTI SKID INOPERATIVE (FLAPS 40)	VREF40	1630	105/-110	45/60	-85	310	60	-50	120
HYDRAULICS - LOSS OF SYSTEM A (FLAPS 15)	VREF15	1445	90/-95	40/55	-60	215	40	-35	125
HYDRAULICS - LOSS OF SYSTEM A (FLAPS 30)	VREF30	1370	85/-90	35/50	-60	210	35	-30	125
HYDRAULICS - LOSS OF SYSTEM A (FLAPS 40)	VREF40	1300	80/-85	35/45	-60	205	35	-30	125
HYDRAULICS - LOSS OF SYSTEM B (FLAPS 15)	VREF15	1295	80/-80	35/45	-55	200	30	-25	95
HYDRAULICS - MANUAL REVERSION (LOSS OF BOTH SYSTEM A & B)	VREF15	1720	100/-110	45/60	-70	245	55	-50	175
LEADING EDGE FLAPS TRANSIT	VREF15+15	1395	80/-85	35/50	-60	205	30	-25	90
ONE ENGINE INOPERATIVE (FLAPS 15)	VREF15	1290	75/-80	30/45	-55	200	30	-25	90
ONE ENGINE INOPERATIVE (FLAPS 30)**	VREF30	1230	70/-75	30/40	-55	195	30	-25	90

Reference distance assumes sea level, standard day, with no wind or slope.
Actual (unfactored) distances are shown.
Includes distance from 50 ft above runway threshold (305 m of air distance).
Assumes maximum manual braking and maximum reverse thrust when available on operating engine(s).
Altitude adjustment for STD altitudes valid up to 8000 ft pressure altitude.
Altitude adjustment for HIGH altitudes valid for altitudes above 8000 ft up to 14000 ft.

***For landing distance above 8000 ft pressure altitude, first apply the STD altitude adjustment to derive new reference landing distance for 8000 ft, then apply applicable HIGH altitude adjustment between 8000 ft and 14000 ft to this new reference distance.**

****ONE ENGINE INOPERATIVE (FLAPS 30) data are only applicable to Fail Operational airplanes.**

ADVISORY INFORMATION

Non-Normal Configuration Landing Distance

Good Reported Braking Action

LANDING CONFIGURATION	VREF	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: HEAD WIND	WIND ADJ PER 10 KTS: TAIL WIND	SLOPE ADJ PER 1%: DOWN HILL	SLOPE ADJ PER 1%: UP HILL	APP SPD ADJ PER 10 KTS ABOVE VREF
STABILIZER TRIM INOPERATIVE	VREF15	1240	75/-75	30/45	-55	190	25	-25	85
JAMMED OR RESTRICTED FLIGHT CONTROLS	VREF15	1240	75/-75	30/45	-55	190	25	-25	85
TRAILING EDGE FLAP ASYMMETRY (30 ≤ FLAPS < 40)	VREF30	1190	70/-70	30/40	-55	185	25	-25	85
TRAILING EDGE FLAP ASYMMETRY (15 ≤ FLAPS < 30)	VREF15	1240	75/-75	30/45	-55	190	25	-25	85
TRAILING EDGE FLAP ASYMMETRY (1 ≤ FLAPS < 15)	VREF40+30	1370	75/-80	35/45	-55	200	25	-25	80
TRAILING EDGE FLAP DISAGREE (30 ≤ FLAPS < 40)	VREF30	1190	70/-70	30/40	-55	185	25	-25	85
TRAILING EDGE FLAP DISAGREE (15 ≤ FLAPS < 30)	VREF15	1240	75/-75	30/45	-55	190	25	-25	85
TRAILING EDGE FLAP DISAGREE (1 ≤ FLAPS < 15)	VREF40+30	1370	75/-80	35/45	-55	200	25	-25	80
TRAILING EDGE FLAPS UP	VREF40+40	1465	80/-85	40/50	-60	205	30	-25	80

Reference distance assumes sea level, standard day, with no wind or slope.
Actual (unfactored) distances are shown.
Includes distance from 50 ft above runway threshold (305 m of air distance).
Assumes maximum manual braking and maximum reverse thrust when available on operating engine(s).
Altitude adjustment for STD altitudes valid up to 8000 ft pressure altitude.
Altitude adjustment for HIGH altitudes valid for altitudes above 8000 ft up to 14000 ft.

***For landing distance above 8000 ft pressure altitude, first apply the STD altitude adjustment to derive new reference landing distance for 8000 ft, then apply applicable HIGH altitude adjustment between 8000 ft and 14000 ft to this new reference distance.**

ADVISORY INFORMATION

Non-Normal Configuration Landing Distance

Medium Reported Braking Action

LANDING CONFIGURATION	VREF	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
					HEAD WIND	TAIL WIND	DOWN HILL	UP HILL	PER 10 KTS ABOVE VREF
ALL FLAPS UP	VREF40+55	2275	145/-150	75/100	-100	360	80	-70	115
ANTI SKID INOPERATIVE (FLAPS 40)	VREF40	2055	145/-150	65/85	-125	490	135	-100	140
HYDRAULICS - LOSS OF SYSTEM A (FLAPS 15)	VREF15	1975	145/-150	65/85	-100	350	90	-75	160
HYDRAULICS - LOSS OF SYSTEM A (FLAPS 30)	VREF30	1855	135/-135	60/80	-95	340	85	-70	155
HYDRAULICS - LOSS OF SYSTEM A (FLAPS 40)	VREF40	1745	125/-125	55/75	-90	330	80	-70	155
HYDRAULICS - LOSS OF SYSTEM B (FLAPS 15)	VREF15	1770	125/-125	55/75	-90	325	70	-60	125
HYDRAULICS - MANUAL REVERSION (LOSS OF BOTH SYSTEM A & B)	VREF15	2380	165/-165	75/100	-115	395	120	-100	215
LEADING EDGE FLAPS TRANSIT	VREF15+15	1900	130/-130	60/80	-90	335	70	-60	115
ONE ENGINE INOPERATIVE (FLAPS 15)	VREF15	1835	125/-130	55/70	-95	345	80	-70	130
ONE ENGINE INOPERATIVE (FLAPS 30)**	VREF30	1725	115/-120	50/65	-90	330	80	-65	125

Reference distance assumes sea level, standard day, with no wind or slope.
Actual (unfactored) distances are shown.
Includes distance from 50 ft above runway threshold (305 m of air distance).
Assumes maximum manual braking and maximum reverse thrust when available on operating engine(s).
Altitude adjustment for STD altitudes valid up to 8000 ft pressure altitude.
Altitude adjustment for HIGH altitudes valid for altitudes above 8000 ft up to 14000 ft.

***For landing distance above 8000 ft pressure altitude, first apply the STD altitude adjustment to derive new reference landing distance for 8000 ft, then apply applicable HIGH altitude adjustment between 8000 ft and 14000 ft to this new reference distance.**

****ONE ENGINE INOPERATIVE (FLAPS 30) data are only applicable to Fail Operational airplanes.**

ADVISORY INFORMATION

Non-Normal Configuration Landing Distance

Medium Reported Braking Action

LANDING CONFIGURATION	VREF	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
					HEAD WIND	TAIL WIND	DOWN HILL	UP HILL	PER 10 KTS ABOVE VREF
STABILIZER TRIM INOPERATIVE	VREF15	1690	115/-120	50/70	-85	315	65	-55	115
JAMMED OR RESTRICTED FLIGHT CONTROLS	VREF15	1690	115/-120	50/70	-85	315	65	-55	115
TRAILING EDGE FLAP ASYMMETRY (30 ≤ FLAPS < 40)	VREF30	1600	110/-110	45/60	-85	310	60	-55	110
TRAILING EDGE FLAP ASYMMETRY (15 ≤ FLAPS < 30)	VREF15	1690	115/-120	50/70	-85	315	65	-55	115
TRAILING EDGE FLAP ASYMMETRY (1 ≤ FLAPS < 15)	VREF40+30	1885	120/-125	60/80	-90	330	70	-60	110
TRAILING EDGE FLAP DISAGREE (30 ≤ FLAPS < 40)	VREF30	1600	110/-110	45/60	-85	310	60	-55	110
TRAILING EDGE FLAP DISAGREE (15 ≤ FLAPS < 30)	VREF15	1690	115/-120	50/70	-85	315	65	-55	115
TRAILING EDGE FLAP DISAGREE (1 ≤ FLAPS < 15)	VREF40+30	1885	120/-125	60/80	-90	330	70	-60	110
TRAILING EDGE FLAPS UP	VREF40+40	2040	130/-135	65/85	-95	345	75	-65	115

Reference distance assumes sea level, standard day, with no wind or slope.
Actual (unfactored) distances are shown.
Includes distance from 50 ft above runway threshold (305 m of air distance).
Assumes maximum manual braking and maximum reverse thrust when available on operating engine(s).
Altitude adjustment for STD altitudes valid up to 8000 ft pressure altitude.
Altitude adjustment for HIGH altitudes valid for altitudes above 8000 ft up to 14000 ft.

***For landing distance above 8000 ft pressure altitude, first apply the STD altitude adjustment to derive new reference landing distance for 8000 ft, then apply applicable HIGH altitude adjustment between 8000 ft and 14000 ft to this new reference distance.**

ADVISORY INFORMATION

Non-Normal Configuration Landing Distance

Poor Reported Braking Action

LANDING CONFIGURATION	VREF	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 HEAD WIND	WIND ADJ PER 10 KTS TAIL WIND	SLOPE ADJ PER 1% DOWN HILL	SLOPE ADJ PER 1% UP HILL	APP SPD ADJ PER 10 KTS ABOVE VREF
ALL FLAPS UP	VREF40+55	3015	215/-220	110/145	-150	570	190	-145	145
ANTI SKID INOPERATIVE (FLAPS 40)	VREF40	2725	215/-210	90/135	-205	900	480	-235	155
HYDRAULICS - LOSS OF SYSTEM A (FLAPS 15)	VREF15	2555	210/-205	95/130	-145	545	195	-145	190
HYDRAULICS - LOSS OF SYSTEM A (FLAPS 30)	VREF30	2375	190/-185	85/115	-140	530	180	-135	175
HYDRAULICS - LOSS OF SYSTEM A (FLAPS 40)	VREF40	2230	175/-175	75/105	-135	520	175	-130	170
HYDRAULICS - LOSS OF SYSTEM B (FLAPS 15)	VREF15	2300	180/-175	80/110	-135	515	160	-120	150
HYDRAULICS - MANUAL REVERSION (LOSS OF BOTH SYSTEM A & B)	VREF15	3055	235/-230	105/150	-165	600	240	-185	240
LEADING EDGE FLAPS TRANSIT	VREF15+15	2450	185/-185	85/115	-135	520	160	-120	135
ONE ENGINE INOPERATIVE (FLAPS 15)	VREF15	2505	190/-190	80/110	-150	560	205	-150	160
ONE ENGINE INOPERATIVE (FLAPS 30)**	VREF30	2320	170/-175	75/100	-140	540	190	-140	150

Reference distance assumes sea level, standard day, with no wind or slope.
Actual (unfactored) distances are shown.
Includes distance from 50 ft above runway threshold (305 m of air distance).
Assumes maximum manual braking and maximum reverse thrust when available on operating engine(s).
Altitude adjustment for STD altitudes valid up to 8000 ft pressure altitude.
Altitude adjustment for HIGH altitudes valid for altitudes above 8000 ft up to 14000 ft.

***For landing distance above 8000 ft pressure altitude, first apply the STD altitude adjustment to derive new reference landing distance for 8000 ft, then apply applicable HIGH altitude adjustment between 8000 ft and 14000 ft to this new reference distance.**

****ONE ENGINE INOPERATIVE (FLAPS 30) data are only applicable to Fail Operational airplanes.**

ADVISORY INFORMATION

Non-Normal Configuration Landing Distance

Poor Reported Braking Action

		LANDING DISTANCE AND ADJUSTMENT (M)							
					WIND ADJ PER 10 KTS		SLOPE ADJ PER 1%		APP SPD ADJ
LANDING CONFIGURATION	VREF	REF DIST FOR 60000 KG LANDING WEIGHT	WT ADJ PER 5000 KG ABV/BLW 60000 KG	ALT ADJ PER 1000 FT STD/HIGH*	HEAD WIND	TAIL WIND	DOWN HILL	UP HILL	PER 10 KTS ABOVE VREF
STABILIZER TRIM INOPERATIVE	VREF15	2195	170/-165	75/100	-130	500	150	-110	135
JAMMED OR RESTRICTED FLIGHT CONTROLS	VREF15	2195	170/-165	75/100	-130	500	150	-110	135
TRAILING EDGE FLAP ASYMMETRY (30 ≤ FLAPS < 40)	VREF30	2060	155/-155	65/95	-125	485	140	-105	130
TRAILING EDGE FLAP ASYMMETRY (15 ≤ FLAPS < 30)	VREF15	2195	170/-165	75/100	-130	500	150	-110	135
TRAILING EDGE FLAP ASYMMETRY (1 ≤ FLAPS < 15)	VREF40+30	2465	180/-180	85/115	-135	520	160	-120	135
TRAILING EDGE FLAP DISAGREE (30 ≤ FLAPS < 40)	VREF30	2060	155/-155	65/95	-125	485	140	-105	130
TRAILING EDGE FLAP DISAGREE (15 ≤ FLAPS < 30)	VREF15	2195	170/-165	75/100	-130	500	150	-110	135
TRAILING EDGE FLAP DISAGREE (1 ≤ FLAPS < 15)	VREF40+30	2465	180/-180	85/115	-135	520	160	-120	135
TRAILING EDGE FLAPS UP	VREF40+40	2680	190/-195	95/130	-145	540	170	-130	140

Reference distance assumes sea level, standard day, with no wind or slope.
Actual (unfactored) distances are shown.
Includes distance from 50 ft above runway threshold (305 m of air distance).
Assumes maximum manual braking and maximum reverse thrust when available on operating engine(s).
Altitude adjustment for STD altitudes valid up to 8000 ft pressure altitude.
Altitude adjustment for HIGH altitudes valid for altitudes above 8000 ft up to 14000 ft.

***For landing distance above 8000 ft pressure altitude, first apply the STD altitude adjustment to derive new reference landing distance for 8000 ft, then apply applicable HIGH altitude adjustment between 8000 ft and 14000 ft to this new reference distance.**

D

Questionnaires

The experiment described in Chapter 6 asked participants about their decisions and the factors that influenced them. These responses were collected through surveys, which participants could complete either by speaking out loud or using the touchscreen interface.

A short survey followed each scenario, and a final one gathered overall feedback on usability and user preferences.

The actual questions used in the study are included in this appendix.

D.1. Post Scenario Survey

Displaytype

What flight deck setup was presented to you?

Conventional   Concept

Speakout 1

Speak clearly while answering the following question:

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

Speakout 2

Speak clearly while answering the following question:

Please describe what factors you take into account for the remainder of the flight.

Speakout 3

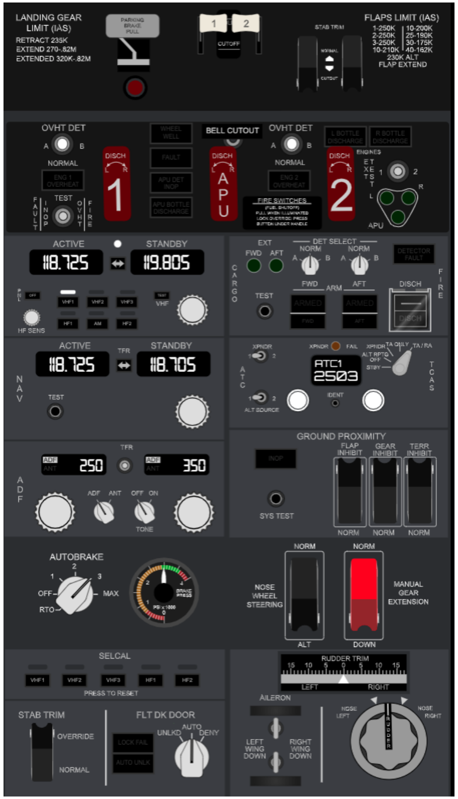
Speak clearly while answering the following question:

Would you change the current flight plan? If so, how and why?

System Status

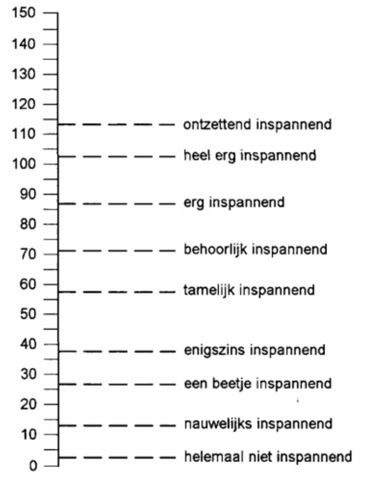
Please indicate which changes in alert lights or system indications you observed on the overhead panel. Do this by tapping on the location you observed the change.

You can press maximum 10 changes, in case you want more mention them out loud. If you want to remove one, tap again and the point will disappear.



Experienced Workload

Please indicate how you experienced the workload during the scenario by tapping on the scale below.



Landing site

Specify your final decision:

At which of the following airports are you planning to land?

- REDMOUNTAIN INTL (IRDM)
- OATPEAKS INTL (IOPK)
- WILLOWFORT RNGL (IWLF)
- DRYSTONE INTL (IDST)
- WARMHILL INTERCONTINENTAL (IWLL)

Specify your final decision:

At which of the following runways at REDMOUNTAIN (IRDM) are you planning to land?

- RWY 12
- RWY 30
- RWY 8
- RWY 26

Specify your final decision:

Which of the following approach procedures would you plan at REDMOUNTAIN (IRDM) for runway 12?

- ILS RWY 12
- RNAV (RNP) Z RWY 12
- RNAV (GPS) Y RWY 12
- VOR circling
- Visual

Specify your final decision:

Which of the following approach procedures would you plan at REDMOUNTAIN (IRDM) for runway 30?

- RNAV (GPS) RWY 30
- Visual

Specify your final decision:

Which of the following approach procedures would you plan at REDMOUNTAIN (IRDM) for runway 26?

- VOR circling
- Visual

Specify your final decision:

Which of the following approach procedures would you plan at REDMOUNTAIN (IRDM) for runway 08?

- VOR circling
- Visual

Specify your final decision:

At which of the following runways at OATPEAKS (IOPK) are you planning to land?

- RWY 3
- RWY 21
- RWY 8
- RWY 26

Specify your final decision:

Which of the following approach procedures would you plan at OATPEAKS (IOPK) for runway 03?

- ILS or LOC RWY 3
- ILS RWY 3 CAT II
- ILS RWY 3 CAT III
- RNAV (RNP) Z RWY 3
- RNAV (GPS) Y RWY 3
- Visual

Specify your final decision:

Which of the following approach procedures would you plan at OATPEAKS (IOPK) for runway 21?

- ILS or LOC RWY 21
- ILS RWY 21 CAT II
- ILS RWY 21 CAT III
- RNAV (GPS) RWY 21
- Visual

Specify your final decision:

Which of the following approach procedures would you plan at OATPEAKS (IOPK) for runway 8?

- RNAV (GPS) RWY 8
- Visual

Specify your final decision:

Which of the following approach procedures would you plan at OATPEAKS (IOPK) for runway 26?

- RNAV (GPS) RWY 26
- Visual

Specify your final decision:

At which of the following runways at DRYSTONE (IDST) are you planning to land?

- RWY 3
- RWY 21
- RWY 8
- RWY 26

Specify your final decision:

Which of the following approach procedures would you plan at DRYSTONE (IDST) for runway 3?

- ILS or LOC RWY 3
- RNAV (GPS) RWY 3
- Visual

Specify your final decision:

Which of the following approach procedures would you plan at DRYSTONE (IDST) for runway 21?

- RNAV (GPS) RWY 21
- VOR/DME RWY 21
- Visual

Specify your final decision:

Which of the following approach procedures would you plan at DRYSTONE (IDST) for runway 8?

- RNAV (GPS) RWY 8
- Visual

Specify your final decision:

Which of the following approach procedures would you plan at DRYSTONE (IDST) for runway 26?

- RNAV (GPS) RWY 26
- Visual

Specify your final decision:

At which of the following runways at WILLOWFORT (IWLF) are you planning to land?

- RWY 9
- RWY 27
- RWY 3
- RWY 21

Specify your final decision:

Which of the following approach procedures would you plan at WILLOWFORT (IWLF) for runway 09?

- RNAV (GPS) RWY 9
- VOR RWY 9 circling
- Visual

Specify your final decision:

Which of the following approach procedures would you plan at WILLOWFORT (IWLF) for runway 27?

- RNAV (GPS) RWY 27
- ILS or LOC RWY 27
- Visual

Specify your final decision:

At which of the following runways at WARMHILL INTERCONTINENTAL (IWLL) are you planning to land?

- RWY 8L
- RWY 8R
- RWY 9
- RWY 15L
- RWY 15R
- RWY 26R
- RWY 26L
- RWY 27
- RWY 33L
- RWY 33R

What AUTOBRAKE setting are you planning for?

- Manual
- Autobrake 1
- Autobrake 2
- Autobrake 3
- Autobrake MAX

What FLAP setting are you planning for?

- 0
- 15
- 20
- 30
- 40

What will be the required landing distance in meters at your planned landing site with your planned landing configuration?

0 1000 2000 3000 4000

Landing distance required in meters

SA

How would you assess the risk involved, in terms of flight safety, if you would execute the following maneuvers while considering the happened events in the last scenario?

	Very Small	Small	Medium	Large	Severe
Land at REDMOUNTAIN (IRDM)	○	○	○	○	○
Flying a RNAV (GPS) approach	○	○	○	○	○
Landing with crosswind component above 30 KTS	○	○	○	○	○
Land at WILLOWFORT (IWLF)	○	○	○	○	○
Turn back to IWLL	○	○	○	○	○
Fly through icing conditions	○	○	○	○	○
Fly for longer than 60 minutes	○	○	○	○	○
Flying a RNAV (RNP) approach	○	○	○	○	○
Emergency Descent to 10000 ft	○	○	○	○	○
Flying a ILS CAT II approach	○	○	○	○	○
Flying a ILS CAT III approach	○	○	○	○	○
Flying through turbulence	○	○	○	○	○
Divert to OATPEAKS (IOPK)	○	○	○	○	○

D.2. Final Survey

TU Delft

Block 1

In how many of you daily operations do you come across disruptions in-flight?

- 100% of my flights
- 90% of my flights
- 80% of my flights
- 70% of my flights
- 60% of my flights
- 50% of my flights
- 40% of my flights
- 30% of my flights
- 20% of my flights
- 10% of my flights
- 5% of my flights
- Never

Of all your experienced in-flight disruptions events, how often were the following events or elements a contributing factor?

	Always	Most of the time	About half the time	Sometimes	Never
Ground handling event	○	○	○	○	○
A/C Malfunctions	○	○	○	○	○
Terrain	○	○	○	○	○
Operational Pressure	○	○	○	○	○
Traffic	○	○	○	○	○
ATC command	○	○	○	○	○
Airport Conditions	○	○	○	○	○
Weather	○	○	○	○	○
Passenger event	○	○	○	○	○

How easy, to your opinion, is it to check the weather information on airports?

- Extremely easy
- Somewhat easy
- Neither easy nor difficult
- Somewhat difficult
- Extremely difficult

How easy, to your opinion, is it to check the aerodrome information using NOTAMs?

- Extremely easy
- Somewhat easy
- Neither easy nor difficult
- Somewhat difficult
- Extremely difficult

How easy, to your opinion, is it to extract the airplanes status and the consequences on the flight from the current supports?

For example if autoland is still working or if you can fly a CAT III approach.

- Extremely easy
- Somewhat easy
- Neither easy nor difficult
- Somewhat difficult
- Extremely difficult

Speak clearly while answering the following question:

What systems or system performance are required to perform a RNAV (GPS) to regulations? And a RNAV (RNP) approach?

Product Concept Testing

How positive are you towards an introduction of new support tools / interfaces on the current flightdeck?

- Extremely positive
- Somewhat positive
- Neither positive nor negative
- Somewhat negative
- Extremely negative

What is your initial reaction to this concept?

- Extremely positive
- Somewhat positive
- Neither positive nor negative
- Somewhat negative
- Extremely negative

How useful would you say this concept is during your day to day operation? Is there a need for this concept?

- Extremely useful
- Very useful
- Moderately useful
- Slightly useful
- Not at all useful

How much do you like or dislike the visualization of space and path conflicts (i.e. the amber lines and shapes)?

- Like a great deal
- Like somewhat
- Neither like nor dislike
- Dislike somewhat
- Dislike a great deal

Does this concept contribute, to your opinion, to a increased level of safety?

- Definitely yes
- Probably yes
- Might or might not
- Probably not
- Definitely not

Did the concept provide you with unexpected insights?

- Definitely yes
- Probably yes
- Might or might not
- Probably not
- Definitely not

Speak clearly while answering the following question:

What unexpected insights did you came across?

Please indicate roughly how much you used the concept displays:

	A great deal	A lot	A moderate amount	A little	None at all
Task list	○	○	○	○	○
System functional overview	○	○	○	○	○
Time velocity situation display	○	○	○	○	○
Vertical situation display	○	○	○	○	○
Horizontal situation display	○	○	○	○	○

Please indicate how clear you found the concept displays:

	Extremely clear	Somewhat clear	Neither clear nor unclear	Somewhat unclear	Extremely unclear
Task list	○	○	○	○	○
System functional overview	○	○	○	○	○
Time velocity situation display	○	○	○	○	○
Vertical situation display	○	○	○	○	○
Horizontal situation display	○	○	○	○	○

Please indicate how you liked the following displays:

	Like a great deal	Like somewhat	Neither like nor dislike	Dislike somewhat	Dislike a great deal
Task list	○	○	○	○	○
System functional overview	○	○	○	○	○
Time velocity situation display	○	○	○	○	○

	Like a great deal	Like somewhat	Neither like nor dislike	Dislike somewhat	Dislike a great deal
Vertical situation display	○	○	○	○	○
Horizontal situation display	○	○	○	○	○
Conventional electronic checklist	○	○	○	○	○

How realistic were the scenarios presented to you in the experiment?

	Extremely realistic	Somewhat realistic	Neither realistic nor unrealistic	Somewhat unrealistic	Extremely unrealistic
Scenario 1, Cargo Fire	○	○	○	○	○
Scenario 2, Wing body overheat	○	○	○	○	○
Scenario 3, Hydraulic Leak	○	○	○	○	○
Scenario 4, Electrical failure	○	○	○	○	○

Speak clearly while answering the following question:

What do you like MOST about this concept?

Speak clearly while answering the following question:

What do you like LEAST about this concept?

Curriculum Vitæ

Jelmer Pascal REITSMA

21-05-1991	Born in Grootegast, The Netherlands.

Education

2017-2022 PhD. Aerospace Engineering
Delft University of Technology
Thesis: Elevated Levels of Automation for Aircraft System & Flight Plan Management
Promotors: Dr. ir. M.M. van Paassen
Dr. ir. C. Borst

2013–2016 MSc Aerospace Engineering
Delft University of Technology

2009–2013 BSc Aerospace Engineering
Delft University of Technology

Experience

2022-now Business to Technical Specialist
The Boeing Company, Neu-Isenburg, Germany

2016-2017 Human System Engineer
Boeing Research & Technology Europe, Madrid, Spain

2015-2016 Graduation Student Engineer
Boeing Research & Technology Europe, Madrid, Spain

2014-2015 Engineering Intern
Boeing Research & Technology Europe, Madrid, Spain

2013-2015 Junior Engineer
Barge Master BV, Capelle a/d IJssel, The Netherlands

List of Publications

7. M. M. van Paassen, **J.P. Reitsma**, E-J Huijbrechts, C. Borst, A. Landman, M. Mulder, *The Skill Assumption: Over-Relicance on Perception Skills in Hazard Analysis*, Proceedings of the 21th International Symposium on Aviation Psychology (ISAP 2021), pp. 322-327 (2021).

6. C. E. Linskens, **J.P. Reitsma**, C.Borst, M. M. van Paassen, M. Mulder, *A Novel Automated Electronic Checklist for Non-Normal Event Resolution Tasks*, AIAA Scitech 2021 Forum: 11–15 & 19–21 January 2021, Virtual Event. American Institute of Aeronautics and Astronautics Inc. (AIAA) (2021).

5. **J.P. Reitsma**, M. M. van Paassen, C. Borst, M. Mulder *Quantifying Automatable Checklist Items on a Commercial Flightdeck*, AIAA Scitech 2021 Forum: 11–15 & 19–21 January 2021, Virtual Event. American Institute of Aeronautics and Astronautics Inc. (AIAA) (2021).

4. **J.P. Reitsma**, M.M. van Paassen, M. Mulder, *Operational Alerting Concept for Commercial Single Pilot Operations Systems*, Proceedings of the 20th International Symposium on Aviation Psychology (ISAP 2019) (2019).

3. **J.P. Reitsma**, M.M. van Paassen, M. Mulder *Operational Alerting on Modern Commercial Flight Decks*, Proceedings of the 20th International Symposium on Aviation Psychology (ISAP 2019) (2019).

2. **J.P. Reitsma**, M.M. van Paassen, M. Mulder *Methodology Comparison for Designing a Decision-making Support System*, Proceedings of the 14th IFAC Symposium on Analysis, Design, and Evaluation of Human Machine Systems HMS 2019, pp. 157-162 (2019).

1. **J.P. Reitsma**, L. Fucke, C. Borst, M.M. van Paassen *Taking a Closer Look at Flight Crew Handling of Complex Failures: Ten Case Studies*, Proceedings of the 19th International Symposium on Aviation Psychology (ISAP 2017), pp. 560–565 (2017).

Propositions

accompanying the dissertation

Elevated Levels of Automation for Aircraft System & Flight Plan Management

by

Jelmer P. Reitsma

1. Pilots should be aided with clear operational alerts to manage flight disturbances, not burdened with tasks like pump switching or cryptic abbreviations. (this thesis)
2. System tasks can be effectively allocated to automation without significant negative impacts, provided that in-flight contingency planning is supported. (this thesis)
3. The integration of high-integrity information with unreliable external sources can lead to the dismissal of critical safety alerts, potentially resulting in a loss of trust in the entire system. (this thesis)
4. While improving data reliability is vital, complete accuracy is unattainable, making critical thinking essential in pilot training. (this thesis)
5. Open-source software is a fundamental pillar of modern scientific innovation.
6. The trade-off between skill degradation and productivity will remain a persistent challenge in automation design for the foreseeable future.
7. The primary focus of inflight decision-making should not be on speed; instead, the goal should be to make informed decisions.
8. Achieving comprehensive expertise in a multidisciplinary field is inherently difficult and may ultimately be an unattainable goal.
9. Decisions based purely on economic motives are similar to automation; both are helpful but can be dangerous if followed blindly.
10. The implications of COVID-19 highlighted an extreme use case for destroying operating space and paths.

These propositions are regarded as opposable and defendable, and have been approved as such by the promotors dr. ir. M.M. van Paassen and dr. ir. C.Borst.