Faculty of Aerospace Engineering

Single Pilot Commercial Operations

A Study of the Technical Hurdles

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Delft
University of
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Challenge the future

Single Pilot Commercial Operations

A Study of the Technical Hurdles

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The undersigned hereby certify that they have read and recommend to the Faculty of Aerospace Engineering for acceptance a thesis entitled **“Single Pilot Commercial Operations”** by **A. Faber** in partial fulfillment of the requirements for the degree of **Master of Science**.

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Abstract

History has shown that a larger flight crew does not per se imply that aircraft operations will be safer. The goal of this thesis is to determine the technical hurdles to Single Pilot Commercial Operations (SPCO). Continued technological developments, the upsurge of commercial Unmanned Aerial Systems, the non-negligible cost of air crews, and yet, stagnation in commercial crew reductions since 1980 are reasons to clarify the current technical hurdles to SPCO. The research was initiated with a broad literature survey. It was found that advances in technology and human factors understanding have made each historical crew reduction possible, through a redistribution of tasks across (fewer) humans, automation, supporting infrastructure and accompanying procedures. An exhaustive list was then formulated of all issues that could potentially affect a reduction to SPCO. Consequently, in-depth research of each issue determined the most predominant challenges to SPCO are; a. providing the single pilot with the correct situational awareness at a manageable workload; b. ensuring adequate monitoring of pilot performance without an on-board human co-pilot; and c. ensuring redundancy in case of incapacitation. Finally, Single Pilot Incapacitation Redundancy (SPIR) solutions were explored by means of a scenario analysis and functional analysis. The greatest challenge to SPIR turns out to be the setting of the incapacitation detection sensitivity threshold; avoiding excessive false warnings (alarm problem) yet retaining immediacy for timely recovery of stable flight; both incapacitation detection and seem-less control take-over are tasks more suited to the adaptability of humans. A concept for a SPCO flight deck has been presented in which these issues become obsolete.

Acronyms

AA	Adaptive Automation
ADS-B	Automatic Dependent Surveillance-Broadcast
AFM	Aircraft Flight Manual
ALPA	Air Line Pilots Association
AOPA	Aircraft Owners and Pilots Association
ASTRAEA	Autonomous Systems Technology Related Airborne Evaluation & Assessment
ATC	Air Traffic Control
ATCO	Air Traffic Control Officer
ATM	Air Traffic Management
ATS	Air Transport System
ATSB	Australian Transport Safety Bureau
CAA	Civil Aviation Authority
CAB	Civil Aviation Board
CDA	Continuous Descent Approach
CDTI	Cockpit Display of Traffic Information
CEO	Chief Excecutive Officer
CFRP	Composite Fiber Re-enforced Plastic
ConOps	Concept of Operations
CPDLC	Controller Pilot Data Link Communications
CRT	Cathode Ray Tube
CSE	Cognitive Systems Engineering
CTA	Cognitive Task Analysis
DFDR	Digital Fight Data Recorder
EASA	European Aviation Safety Agency
ECAM	Electronic Centralised Aircraft Monitor
EEG	Electroencephalogram
EFIS	Electronic Flight Information System
EICAS	Engine Indication and Crew Alerting System
EPAM	Electronic Pilot Activity and Alertness Monitor

FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
FBG	Fiber Bragg Grating
FD	Flight Deck
FE	Flight Engineer
FO	First Officer
FMGC	Flight Management Guidance Computer
FMS	Flight Management System
GS	Glide Slope
GPS	Global Positioning System
HF	Human Factors
HMI	Human Machine Interface
HRV	Heart Rate Variability
HUD	Heads Up Display
ICAO	International Civil Aviation Organization
IFR	Instrument Flight Rules
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
INS	Inertial Navigation System
LOSA	Line Operations Safety Audit
LOSA:SP	Line Operations Safety Audit:Single Pilot
MTOW	Maximum Take-Off Weight
NASA	National Aeronautics and Space Administration
NextGen	Next Generation Air Transportation System
OFS	Operator Functional State
PF	Pilot Flying
PM	Performance Monitoring
PNF	Pilot Not Flying
PZT	Piezoelectric Lead Zirconate Titanate
SA	Situational Awareness
SARP	Standard and Recommended Practice
SESAR	Single European Sky ATM Research
SOP	Standard Operating Procedure
SPCO	Single Pilot Commercial Operations
SPFD	Single Pilot (Commercial Operations) Flight Deck
SPIR	Single Pilot Incapacitation Redundancy
SRM	Single Pilot Resource Management
STS	Space Transportation System
SVD	Synthetic Vision Display
SWIM	System Wide Information Management
TCAG	Trans-Cockpit Authority Gradient
TLS	Target Level of Safety
TUC	Time for Useful Consciousness
UAS	Unmanned Aircraft Systems
VCP	Virtual Certification Process
VFR	Visual Flight Rules
VMC	Visual Meteorological Conditions
WL	Workload

Contents

To my grandparents A. Beukers and A. M. Beukers-Wierks.

Chapter 1

Introduction

The minimum size of flight crews for commercial flights has reduced during history, until halting at two in the early 1980's. Whether two pilot commercial flight crews are a convention due to rational design choices or other reasons, is not immediately clear. The global air transport system involves many stakeholders. Its current state is the result of an evolution over time. The primacy of safety and the involvement of (cross-border) regulatory authorities, airlines, and pilot unions in design, have impacted where the system has ended up. The evolution is not purely a result of engineering breakthroughs, but has been driven by the needs of stakeholders and the requirement for backwards compatibility with existing systems. Within this complex system, there has been no further commercial flight crew reduction after the shift to two in 1981; when an impartial US presidential task force including Federal Aviation Administration (FAA), National Aeronautics and Space Administration (NASA), and United States Air Force (USAF) specialists proved that two crew was safer than three (McLucas, 1981), (Fadden, 2010), (Lerner, 1983). Technological advances and improved understanding of human factors within complex sociotechnical systems are reasons to re-examine optimal aircrew size. It may well be that the convention of two pilots has not been challenged due to the large-scale adherence to this standard; it is nevertheless a requirement that aircraft are designed for a two-man crew from the get-go, inducing high uncertainty to any attempt to design and *especially* certify for SPCO. Simply put, all aspects of the air transport industry are oriented towards multi-crew operations. This environment has discouraged research and development towards SPCO. The challenges of workload and situational awareness plaguing multi-crew FDs appear to require more than incremental innovation to be overcome. Just as the shift from three to two crew resulted in improved safety, SPCO may well offer benefits that currently remain hidden due to the unfavorable environment. Initially, it may seem ridiculous to consider that multi-crew issues would be solved by a crew reduction. And yet, due to similar reasoning it took many years to settle the dispute that two crew is actually safer than three. To open the door to SPCO research and the potential gains to follow, the objective of this thesis project is to provide an answer to the question:

> *What technical hurdles prevent the shift from two pilots to one on commercial operations?*

The goal has been to research this, within the context of *current developments* in the global system of air transportation[1]. As a start, this research aims to identify the technical arguments against a single pilot commercial Flight Deck (FD). To achieve this aim, the research question has been broken down in the following sub-questions:

1. *What is the state of the current global air transportation system in relation to SPCO?*
2. *How has the FD and crew complement evolved during the century of aviation?*
3. *What characterises flights that currently permit single crew operation, as opposed to flights requiring multi-crew operations?*
4. *What are the tasks of the commercial flight crew, and why can these tasks not be performed by one pilot?*
5. *How might new technologies help overcome the identified technical hurdles to SPCO in future?*

In answering these sub-questions, this research aims to provide a comprehensive list of the major technical challenges to SPCO. The report is organized in two parts and follows the same order as the aforementioned sub-questions. At first, the drivers of historical crew reductions were researched, followed by the current aviation regulations. This part of the research clarifies the current state of SPCO within the greater context of aviation, and is presented in Part 1A. A divergent research phase followed, allowing all factors affecting crew size to be listed. As each item was researched in depth it was better understood, and would either lead to new relevant issues or turn out to be of lesser importance. Eventually, the list of potential issues was pruned and converged to the predominant technical challenges to SPCO; the topic of Part 1B of this thesis report. Once the main challenges were identified, a focus was laid on one aspect, being that of single pilot incapacitation redundancy. Incapacitation redundancy was chosen as a focus because the research towards situational awareness and workload are already extensive. The most value could be added by looking into the challenge of incapacitation, a topic that could be suitably isolated for an in-depth study. The extent of the incapacitation challenge to SPCO was determined by means of a scenario analysis and exploration of possible solutions; the topic of Part 2. In addition to the sub-questions above, Part 2 aims to answer the following sub-questions:

6. *What functions must an incapacitation redundancy solution for SPCO provide?*
7. *What are the most challenging SPCO incapacitation redundancy functions to provide, and how might the Single Pilot Flight Deck (SPFD) be designed to overcome these obstacles?*

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[1] Current developments in air transportation include advances in ATM to prepare for capacity and safety demands of the future, overhaul of Small Aircraft regulations and developments towards the introduction of commercial UAS to non-segregated airspace. The popularity of (single pilot) VLJs is increasing and several commercial carriers have voiced interest in operating short flights with a single pilot.

Separating the subject matter into parts has allowed portrayal of the challenges to SPCO within the greater aviation context, and subsequently simplified the focus on the specific challenge of incapacitation. Part 2 includes a separate section explaining the respective research methodology applied.

The work will be progressed in the same order as the aforementioned sub-questions. Chapter 2 describes the research methodology in more detail. In Part 1A, Chapter 3 explains the context of this research; the aviation environment and developments in the near future. Chapter 4 provides an overview of the evolution of the FD and crew compliment. Chapter 5 explains which flights are permitted to be operated single-pilot as per FAA and European Aviation Safety Agency (EASA) regulations. In Part 1B, the human factors issues challenging single pilot operations are discussed in Chapter 6. Chapter 7 presents the incapacitation rates of airline pilots and alternative forms of redundancy. Finally, Chapter 8 shortly discusses developments with potential to overcome the technical hurdles to SPCO. The combined conclusion (Chapter 9) to Parts 1A and 1B summarizes the main findings. Of Part 2, Chapter 10 presents the incapacitation challenge to SPCO; describing the incapacitation research methodology, and the possible incapacitation scenarios that might occur. Chapter 11 presents the functional requirements of an incapacitation redundancy solution for SPCO in the form of a Functional Decomposition, and explores a number of conceptual solutions. A number of critical functions are identified that would be highly complex to provide with current flight decks. A concept for a single pilot flight deck is presented for which the incapacitation redundancy functionality would be much simpler to implement. Finally, the conclusions and recommendations to this thesis are the content of Chapter 12.

Chapter 2

Research Methodology Parts 1A and 1B

This chapter explains the research methodology applied in Parts 1A and 1B. The research methodology of Part 2 is explained separately in Section 10-5.

There are many facets of the Air Transport System (ATS) that affect crew size. For this reason a broad approach has been taken to answer the main research question:

> *What technical hurdles prevent the shift from two pilots to one on commercial operations?*

In order for the research to be valuable, the findings must be comprehensive. Consequently, the more significant issues that inhibit SPCOs must receive more attention. To identify these critical issues required a research methodology which consisted of two phases. The *initial phase* of the research was one of a divergent nature; to identify many potential issues (see Section 2-1). The research was divergent, in the sense that the number of topics of interest multiplied; whilst researching a topic, other relevant topics were often recognized. During the divergent research phase, the author became familiar with the nomenclature and academic clustering of research fields. At the end of the divergent stage, the most important issues affecting single pilot flight had been uncovered.

Of the extensive list of issues, the key issues were singled out and researched in greater depth. This marked the converging phase (see Section 2-2). Within this process of diverging and converging, some flexibility was left for iterations based on what was learned. The result of the process is that the most significant factors were fully identified. Furthermore, their relation to, and impact on, the single pilot question are well understood and highlighted in this report.

The multi-faceted, iterative process is most likely to be comprehensive due to the research from various sources and angles. Researching one potential issue would lead to the identification of other potential issues. For instance, analysis of the FAA and EASA regulations has answered the sub-question of which flights are legally single-pilot operable, but in addition has also helped to view the single pilot situation from the perspective of airworthiness. In researching the regulations, it came to light that the regulations are structured according to old assumptions, as will be discussed in Chapter 5. The regulations are in the midst of an overhaul which will affect the certification and operation of single pilot Very Light Jets (VLJs). Thus, the future of SPCO as determined by regulations appears to be in a period of change. This finding was made by the convergent nature of the research; resulting in one topic leading to another. As a result, this methodology has led to an exhaustive list of the main technical hurdles to SPCO.

Alternative research approaches that were more focused from the onset, or would include more measurable quantitative data, were considered. An example is the analysis and comparison of incident and accident rate data of single pilot and multi-crew operations. Yet, alternative research methods contained significant weaknesses. For instance, the work environments of general and commercial aviation are too dissimilar to estimate the safety of SPCO based on a comparison of single and multi-crew general aviation accident rates. Similarly, other proposed methodologies had their shortcomings. Thus, the described diverging-converging approach was deemed most effective for this far-reaching topic; to uncover the key technical hurdles to commercial single pilot operations. Section 2-1 and Section 2-2 discuss the divergent and convergent phases in more detail.

2-1 Divergent Phase - The Brainstorm

The diverging stage of the research is akin to the metaphor of climbing a tree. Higher up the tree, the branches split and there are increasingly more topics to research. From beneath the tree, it is not clear which branches reach the top. The divergent phase of research is explained below.

Firstly, current literature aimed at single pilot operations was explored. This literature appears scattered, and there seems to be no solid research dialogue between institutions. To be certain that future FD designs are based on factual information as opposed to assumptions, it is valuable to clearly identify the technical reasons why commercial flights are not performed by a single pilot.

To best identify the many factors of significance to single pilot operations, the initial phase involved structured brainstorming. First, current fields of potential relevance were listed based on the author's knowledge. Secondly, developments and market forecasts for technology, aerospace, and aviation sectors were considered. The findings were used in the subsequent brainstorm (with pilots), to identify all factors that could impact single pilot design feasibility in future. The entire list is presented in Appendix A. Figure 2-1 illustrates the diverging and converging research process. A number of sub-research topics are included for clarity. At the left side of the figure, is the start of the research. Towards the right, the research draws nearer to completion; only the most important sub-research topics remain. Finally, situational awareness, workload, performance monitoring, and incapacitation remain on the far right side of the figure.

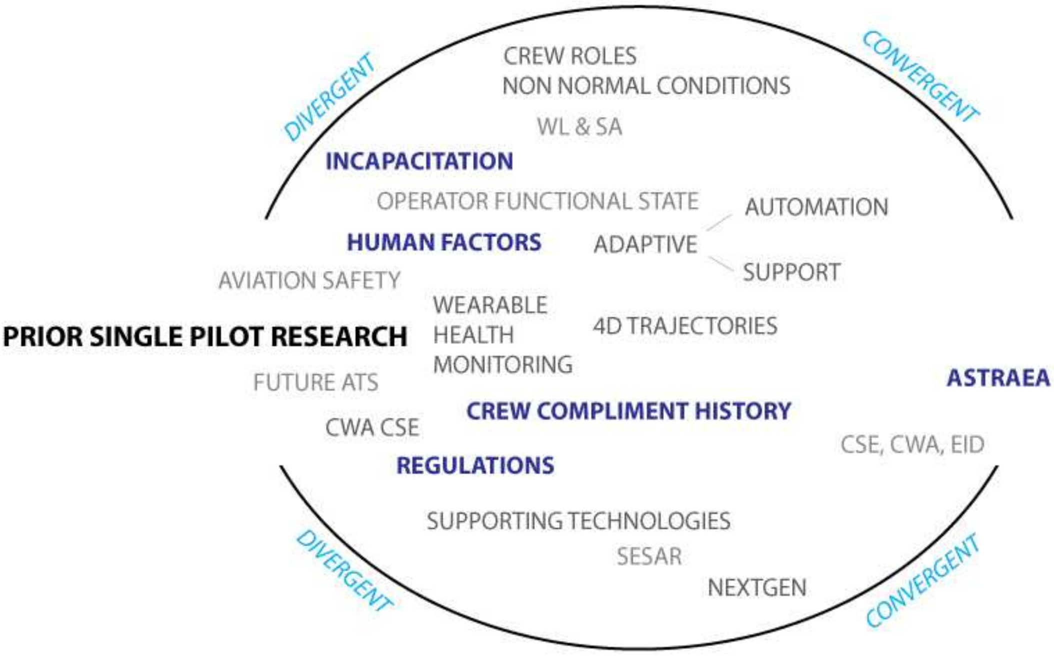


Figure 2-1: Divergent convergent approach

2-2 Convergent Phase - The Shortlist

Referring back to the metaphor of climbing a tree; when viewing the tree from below, it is unclear which of the many branches reach the top. The sturdy branches are the topics of greatest impact to SPCO, and are the foundation for smaller sub-branches; just as the main research topics encompass smaller topics. The aim of the converging phase of the research has been to identify which are the thickest branches that hold up the rest of the tree, that is, the topics that present the greatest technical hurdles to SPCO. During the converging phase of research, the *long-list* was cut down to the *shortlist* of main issues, presented below. The shortlist includes the main technical hurdles, as well as research fields of greatest potential to overcome them.

Shortlist; technical hurdles and potential technological solutions:

- Technical hurdles

  - Situational awareness
  - Workload
  - Performance monitoring
  - Incapacitation of flight crew

- Potential technological solutions
  - Operator Functional State (OFS) measurement (defined in Section 8-3).
  - Adaptive automation and support
  - Autonomous Systems Technology Related Airborne Evaluation & Assessment (ASTRAEA) consortium (see Section 8-1)

The introduction presents five research sub-questions. The order of investigation was not strictly the same as the order in which the findings are presented. The sub-questions were mostly answered as non-definite products of the broader diverging-converging research process. A directed analysis of regulations was aimed to answer the question:

> *What characterises flights that currently permit single crew operation, as opposed to flights requiring multi-crew operations?*

To answer this question, an analysis of regulations in conjunction with the missions of the FAA, EASA, and International Civil Aviation Organization (ICAO) was performed. Because the regulations aim to ensure continued civil aviation safety, such analysis was expected to shed light on the reasoning for multi-crew from a safety perspective. The approach to this separate study is explained together with the findings in Chapter 5. Perhaps surprisingly, the regulations appear to form a design hurdle of bureaucratic nature. Through research of the historical evolution of crew compliment, pilot unions and airlines appeared as other bureaucratic hurdles during the previous century. Although some bureaucratic hurdles were uncovered and mentioned, the research scope is defined to include only technical issues. Thus, public acceptance of single pilot flights and other non-technical issues, have not been the focus of this research.

Significant technical hurdles to single pilot operations in commercial aviation are related to human factors. Workload (WL) is still very high at times (C. D. Wickens, 2002). Situational Awareness (SA) remains to be a significant factor in accidents with human error as causation (Endsley, 1999). Accident causation models alike Reason's Swiss Cheese model (Reason, 1990) support the view that "the pilot is often seen as the last line of defence in preventing an accident" (Rodrigues & Cusick, 2011, p. 148). Performance Monitoring (PM) is still considered a valuable process in the multi-crew flight deck (Halleran, 2010). The risk of incapacitation is a remaining challenge to the realization of sufficiently safe SPCO.

Part 1A

Single Pilot Commercial Operations: The Context of Aviation

Chapter 3

The Context of Aviation

This chapter examines the technical context of the flight deck. The FD is part of a complex sociotechnical system; aviation is time critical, safety critical, *open*, and presents a high dynamic complexity (Rasmussen, 1990). This highlights that the FD cannot be altered without considering the relationship with other systems within aviation. This chapter answers the question:

> *What is the state of the current global air transportation system in relation to SPCO?*

On top of the FD being part of a complex sociotechnical system, the aviation industry is highly fragmented. A variety of different stakeholders are present, each with different goals; thus the design of the FD is influenced by the need to meet these requirements. Sometimes these requirements do not align due to conflicting interests. For example, air crews must control the aircraft, whilst meeting requirements from airline management and from Air Traffic Control (ATC). The fragmentation of the aviation industry is illustrated by the itemization of the major stakeholders below.

- Airlines
- Manufacturers
- Air Traffic Management
- National governments and politics
- Certification and regulatory agencies
- Airports
- Academic institutions

- General public
- Pilots and pilot unions

Based on events in previous eras of innovation in aviation, it appears the global air transport system is once again in a period of change. Increased air space congestion has raised demands of Air Traffic Management (ATM). Next generation Single European Sky ATM Research (SESAR) and Next Generation Air Transportation System (NextGen) aim to prepare ATM systems for the capacity and safety demands of the future. Glass cockpits allow rapid development of new interfaces and automation modes, such as automated separation using Automatic Dependent Surveillance-Broadcast (ADS-B). Adaptive automation is aimed to optimize WL and SA in the mid-term future. Research into Continuous Descent Approach (CDA) is aimed at meeting noise and emissions restrictions. Safety, efficiency, and environmental goals are high on agendas; all challenging ATM. The forecasted rapid increase of civil Unmanned Aerial Systems (UAS) in the next decade (FAA, 2012a), possibly operating in non-segregated airspace, will increase congestion further. The addition of UAS to an airspace, will likely introduce new demands on ATC.

Recent decades have shown a continued study of human factors. Current FD designs appear limited by issues related to WL and SA. The challenge of SA and WL, is that the crew attention is a limited resource; a design change that will improve SA will usually negatively influence the WL (C. D. Wickens, 2008). When the WL is too high, the crew cannot adequately maintain SA as is over-come with an excess of information; too much to process. The situation currently concerning WL and SA is that new interfaces are designed and tested aiming to simultaneously improve both WL and SA. Yet, as Chapter 4 and Chapter 6 explain, it appears that the improvements are becoming smaller; incremental improvements. The glass cockpit has now been around for some time. To make large improvements in SA and WL simultaneously, it seems something bigger has to change. Regulations are also undergoing changes (Bell, 2009).

An adjacent sector, space travel, is undergoing changes too. Retirement of Space Transportation System (STS) (Space Shuttle) and the privatisation of launch systems and space tourism are examples. These changes might be an indication of the onset of a different mindset. Perhaps an attitude is prevailing that is more open to innovative designs.

Conventional cockpit designs appear to have reached a stalemate between WL, SA and level of automation. To maintain current safety rates in increasingly congested airspaces, more radical innovations might be due. At this day and age, a transition to a single crew should be made based on rational analysis of performance and safety, as was the transition from three to two crew. WL and SA are cognitive issues. Hence, Cognitive Systems Engineering (CSE) methods should aid in achieving next-era FD designs to overcome these issues.

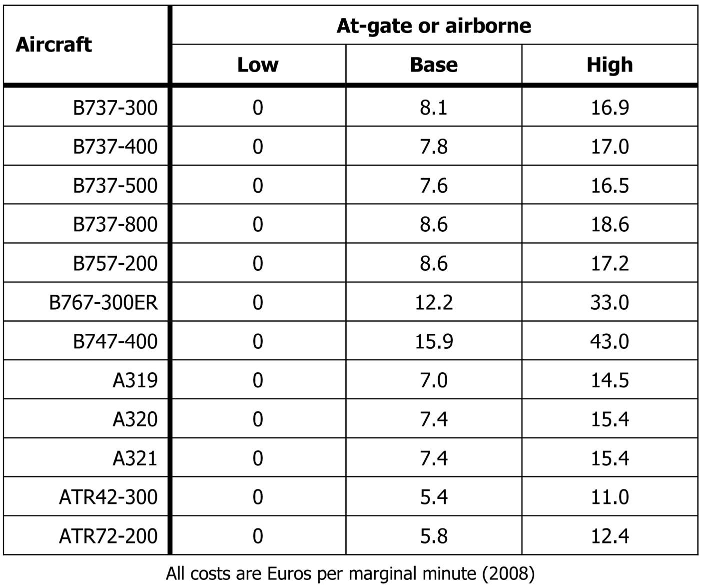
A paper on this topic would not be complete without some mention of the costs of air crews to airlines. As an indication of total labor costs, between 2000 and 2005, United States (US) airline labor costs ranged between 37% and 25% of their total costs, depending on fuel prices (Holloway, 2008). In 2008, EUROCONTROL researched the costs of airline crews. Table 3-1 presents the marginal costs of the total crew (flight plus cabin), per minute (TSG, 2008, p. 11). *Low* and *High* refer to low-cost and flag-carrier airlines respectively. The marginal costs of a B747-400 crew, was up to €43 per minute (TSG, 2008). The marginal costs per member of the flight crew (excluding on-costs such as pension contributions), are depicted in Table 3-2. It is outside the scope of this research to delve further into the potential cost reductions achievable by a crew reduction to SPCO. The net cost savings would depend on all costs (initial and recurring) required to redesign the FD and supporting systems, services, and procedures for single pilot operations. The figures presented here allow the reader a crude understanding of the potential crew cost reduction alone. The reader is left to research the cost savings in more detail if so desired.

The Chief Executive Officer (CEO) of low-cost carrier RYANAIR expressed interest in single pilot operations of short routes in 2010 (Charette, 2010). Embraer stated in 2010 that a future of single pilot operations could be realistic (Doyle, 2010). J. Albaugh, president and CEO of Boeing Commercial Airplanes, announced in August 2011 that a "pilotless airliner is going to come; it's just a question of when." (Patterson, 2012). Thus, there is certainly an interest in crew reduction in industry.

On the other hand, accident rates of VLJs show single pilot operation of complex high performance aircraft can be prone to high risk. The fatal accident rate of all single-pilot certified Cessna Citations (including both GA and commercial aviation) is 3.7 times greater than all two-crew certified Cessna Citations (Horne, 2008). Since the single pilot certified aircraft are only operated single-pilot part of the time, the actual difference between the rates is even greater. To know how much greater, data on the portion of flight time actually operated single-pilot is needed. The higher accident and incident rates of single piloted VLJs illustrate that a switch to SPCO should not be underestimated.

The introduction of civil UAS into non-segregated airspace brings SPCO one step closer to reality. But first it should be fully understood which technical hurdles prevent SPCO. The findings may benefit future designs of FD and procedures, to overcome current hurdles. This report goes on to highlight the technical hurdles to SPCO. The next chapter reviews the history of flight deck design and crew reductions.

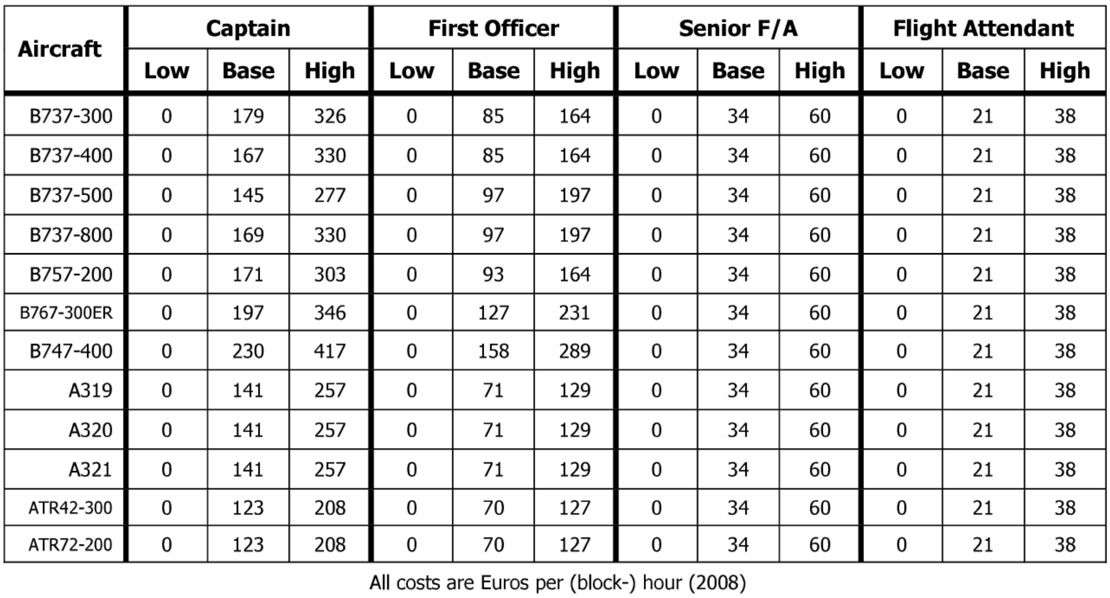
Table 3-1: Marginal crew costs per aircraft, per minute (on-costs included). (TSG, 2008, p. 11)



Aircraft	At-gate or airborne		
	Low	Base	High
B737-300	0	8.1	16.9
B737-400	0	7.8	17.0
B737-500	0	7.6	16.5
B737-800	0	8.6	18.6
B757-200	0	8.6	17.2
B767-300ER	0	12.2	33.0
B747-400	0	15.9	43.0
A319	0	7.0	14.5
A320	0	7.4	15.4
A321	0	7.4	15.4
ATR42-300	0	5.4	11.0
ATR72-200	0	5.8	12.4

All costs are Euros per marginal minute (2008)

Table 3-2: Marginal costs per member of crew (excluding on-costs). (TSG, 2008, p. 10)



Aircraft	Captain			First Officer			Senior F/A			Flight Attendant		
	Low	Base	High	Low	Base	High	Low	Base	High	Low	Base	High
B737-300	0	179	326	0	85	164	0	34	60	0	21	38
B737-400	0	167	330	0	85	164	0	34	60	0	21	38
B737-500	0	145	277	0	97	197	0	34	60	0	21	38
B737-800	0	169	330	0	97	197	0	34	60	0	21	38
B757-200	0	171	303	0	93	164	0	34	60	0	21	38
B767-300ER	0	197	346	0	127	231	0	34	60	0	21	38
B747-400	0	230	417	0	158	289	0	34	60	0	21	38
A319	0	141	257	0	71	129	0	34	60	0	21	38
A320	0	141	257	0	71	129	0	34	60	0	21	38
A321	0	141	257	0	71	129	0	34	60	0	21	38
ATR42-300	0	123	208	0	70	127	0	34	60	0	21	38
ATR72-200	0	123	208	0	70	127	0	34	60	0	21	38

All costs are Euros per (block-) hour (2008)

Chapter 4

Evolution of the Flight Deck and Crew Complement

The previous chapter covered the context of aviation. This chapter shall look specifically at the changes in crew complement throughout history. Any change in crew size is closely linked to the tasks that must be performed on-board. These tasks have changed with supporting technologies, as has the industry philosophy regarding flight deck design and the role of humans.

Roughly three phases of FD design are observed until the 1990's, defined by the level of understanding of human factors and the technologies available at the time. Reductions in the minimum flight crew for safe operations of commercial aircraft have been the result of redistributions of functions. Redistribution has taken place among humans and technology, both on-board and off-board. Due to non-technical influences, flight crews have at times been larger in practice, than the optimal size from the perspective of safety. This chapter answers the question:

> *How has the FD and crew complement evolved during the century of aviation?*

The aim of this chapter is to explain the commercial flight crew reductions throughout history, to better understand the potential future crew reduction to single pilot operations. Section 4-1 illustrates three general phases of FD design until the last crew reduction. Section 4-2 describes the particular role of the Flight Engineer (FE), and the impact of bureaucracy on crew size. Section 4-3 relates the observations to the future of FD design and crew complement. Section 4-4 concludes this chapter.

4-1 Three Phases of Flight Deck Design

Between the 1920's and early 1990's, FD design has seen three phases. This section describes the historical changes in tasks, technology, and crew size during each of the three phases of FD design.

4-1-1 Phase 1: 1920's till the jet era (1950's)

The first phase was one where FDs were designed to the functions of a specific airplane, airline, or route flown. This phase lasted from the 1920's till the jet era. Crew size depended on the tasks to be performed on-board. According to D.M.Fadden, a Boeing engineer during the period,

> "longer missions typically involved more [piston] engines, celestial navigation and erratic radio communications. For these airplanes a crew of five was the norm: two pilots, a flight engineer, a navigator, and a radio operator." (Fadden, 2010).

In this first phase, Human Machine Interface (HMI) design was a trial and error process, based on experiences of pilots and engineers at the manufacturers and airlines.

4-1-2 Phase 2: 1950's till the 1970's

The second phase of FD design is marked by the start of academic research of pilot work load and performance, starting in the 1950's. From this point on the efficiency in FD design increased rapidly. In 1965, Federal Aviation Regulations (FARs) Part 25 was published; enforcing a rational analysis and demonstration of crew performance and workload (Fadden, 2010). Boeing examined the historical performance of aircraft in terms of accidents, incidents, and pilot experiences. FD design objectives for the Boeing 737 were based on the findings. For example, a problem encountered was that the pilots became distracted whilst identifying faults. As a result, Boeing decided to incorporate more reliable systems requiring less in-flight fault management. A similar finding was that sometimes aircraft were spotted too late by pilots, resulting in a series of losses of separation. Boeing engineers compared the performance of three-pilot and two-pilot flight crews. The proportion of potentially hazardous traffic that was spotted before presenting a threat, was compared. The two-pilot crews repeatedly spotted a greater proportion of the potentially hazardous traffic. Thus,

> "the Boeing team became convinced that a two person design for the 737 would be significantly better than a traditional three person crew design". (Fadden, 2010).

From this moment onwards, a commitment was made by Boeing to design the FD for crews of two, whilst knowing that certification would be tougher, and that pilot labor unions would provide resistance. A period of intense resistant lobbying from pilot unions followed. Eventually, in-flight studies of Boeing 737s, in service with three and two man crews, would provide verification that two crew performance was truly safer and more efficient. This marked the end of the second phase in FD design.

4-1-3 Phase 3: 1970's till 1990's

During the third phase of FD design, FD designers knew that the two man crews were safer, yet were resisted by labor unions. In the mid 1970's, during the 767 design, complex integrated circuits allowed automation to be more user-friendly. CRT displays offered new ways to improve situational awareness.

> "[CRTs] also further reduced the small amount of useful workload that could be assigned to a third crew member." (Fadden, 2010). A third crew member would be "an invitation to distraction and, contrary to the intent of the labor unions, could actually cause a decrease in the safety of operations." (Fadden, 2010).

Eventually, in March 1981 a specially assigned US *Presidential Task Force on Aircraft Crew Complement* including NASA, USAF, and FAA specialists, was appointed to investigate the issue of crew complement (McLucas, 1981), (Lerner, 1983). Particularly, the final report from the Presidential Task Force, dating July 2 1981, found that,

> "As designed, the Boeing 757 and 767 aircraft and the A-310 aircraft being developed by the European consortium, Airbus Industrie, potentially can be operated safely by a crew of two. The addition of a third crew member would not be justified in the interest of safety." (McLucas, 1981, p. 2).

From this moment onwards, two crew has been the norm (Lerner, 1983). The B767 and B757, both configured for two crew, first flew in 1981 and 1982 respectively. The Engine Indication and Crew Alerting System (EICAS) and Electronic Flight Information System (EFIS) are displayed on CRT screens, allowing the pilot and co-pilot to complete those tasks previously requiring a third instrument panel (and FE) (Lombardi & Spenser, 2006). From 1985, even the Boeing 747-400 was configured with EICAS, EFIS, and CRTs for a crew of two. In 2008, only a few airlines still operated Boeing 747s with three crew (TSG, 2008).

Since the 1990's, the importance of human factors has been accepted throughout aviation. Greater research into the effect of human interface design on safety has improved safety records. This immense body of research, and the complexities in modern aircraft, rightfully complicate the design decision of crew size.

4-1-4 Lessons learnt

History shows, that a change in crew size is accompanied by a redistribution of tasks throughout the air transport system. A hypothetical reduction to single crew, would again require a redistribution of tasks. Historically, different forms of redistribution of tasks have occurred. For instance, CRT displays have allowed many functions of the FE to be transferred to on-board automation and the pilots. Tasks have been reallocated among humans (on-board or off-board), and technology (on-board and off-board). Communications technologies enabling a redistribution of tasks can be further classified as being; one-way (e.g. Instrument Landing System (ILS), Glide Slope (GS)) or interactive two-way (e.g. ADS-B). Such technologies have played an important part in the shift between FD design phases and crew size. Specific technological advancements and crew reductions are explained in Section 4-2, and listed in Table B-1 in Appendix B.

Three flight deck design phases have been described. At first, FDs were aircraft specific; fitted with instruments for the required functions of the aircraft. From the 1950's, human factors started to have an impact. Starting in 1970, complex integrated circuits enabled more user-friendly automation, making the FE redundant. The following section looks more closely at the changing role of the FE, demonstrating the link between task redistribution and crew reduction.

4-2 The Flight Engineer, Bureaucracy, and Crew Size

The role of the FE has changed throughout history. The first FE's were aboard flying boats, making the first transoceanic flights. The Flight Engineer's role was to "calculate the optimum altitude, airspeed, and power settings" (Harmon, 2006), in order to reach the destination at all. Figure 4-1 shows the Boeing 314 Clipper flying boat, one of the first aircraft to operate commercially across the Atlantic Ocean. The five-man flight crew is displayed at work on the FD in Figure 4-2. The picture shows the clearly separated systems and displays for each of the five crew, as was typical at the time.

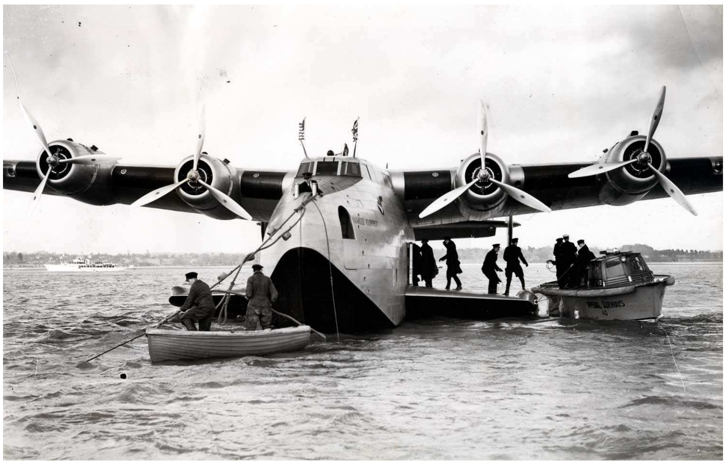


Figure 4-1: Boeing 314 Clipper, courtesy of (lucarelli, 2010)

Figure 4-2: Five-crew Flight Deck of the Boeing 314 Clipper, courtesy of (lucarelli, 2010)

In 1946, the Douglas DC-6 was first introduced. Shortly after, a series of cabin fires led the Civil Aeronautics Board (CAB) to impose the so called 80,000 lb rule. (The CAB was renamed FAA in 1965). The 80,000 lb rule stated that all aircraft over 80,000 lb must have a third crew member. Later the cause of the cabin fires was identified to be a design flaw, yet the rule requiring a FE remained until 1965. This is an example of a situation in which aircraft weight was used (based on a faulty assumption), rather than human factors research, to prescribe a minimum crew size. The FAA finally agreed, in 1965, after years of lobbying, that "simple weight was not a valid criterion for establishment of the need for a third crewmember" (Orlady & Orlady, 1999, p. 50).

Although the 80,000 lb rule was not justified, certain aircraft did require a FE for human factors reasons. On such aircraft, the FE was required to have a greater mechanical and electrical understanding than the pilots, in order to "monitor, troubleshoot and by-pass inoperative components" (Flight, 1957). The increasingly complex systems of the time required a specialist on board to complement the pilots. The "power-plant, the electrical system, the pressurization system, the propeller system, the pneumatic system, the fuel system, and electronics system" each required monitoring of constant nature (Flight, 1957).

The 80,000 lb rule was scrapped when the CAB was converted to the FAA. Electronics had enabled new levels of automation and reliability. At this stage, the impartial presidential task force mentioned previously, found that a FE should be required based on workload and performance analysis. Three crew FDs became rarer. From this stage onwards, technological advances allowed for flight-deck designs that were sufficiently reliable, thus requiring minimal inflight monitoring. Systems were now sufficiently integrated to allow operation and troubleshooting by the pilot and co-pilot. From the late 1970's, flight crew procedures would be integrated into FD design. This is indicative of a shift in task allocation; where previously there was a flight engineer on board to identify and by-pass faults, from then on faults were anticipated during design. Some non-scheduled airlines operating to remote destinations, such as *Polar Air Cargo*, still carried FEs in 1999, partially for the purpose of re-approving the aircraft for operation after maintenance performed at non-base airports (Phillips, 1999). Technological developments and expanding knowledge of human machine interaction, have been the most notable factors enabling the elimination of the FE.

The need for crew complement on current and future modern commercial jet aircraft, would be to provide aid particularly during non-normal conditions, as opposed to routine tasks (as was the role of the FE). In the hypothetical future situation where large commercial aircraft are operated by a crew of one, the environment in which failures could occur will have changed. Automation that would permit the task redistribution to single pilot would be accompanied by new (unanticipated) failure forms (Dekker, 2002). Just as the role of the flight engineer has changed along with the flight-deck, so would the role of the single pilot. Training should provide knowledge of aircraft systems and external supporting systems that could fail.

For many years, a FE was required by law due to bureaucratic influences (lobbying by pilot unions, such as ALPA (Air Line Pilots Association)), rather than by optimal design considerations (Fadden, 2010), (Lerner, 1983). It s remarkable that pilot unions had such an impact, while engineering and pilot experience provided evidence for the contrary. One is inclined to wonder whether ALPA's primary goal was safety or the protection of FE's employment. Pilot unions may well lobby extensively against a move to SPCO. Unfortunately this could result in unsafe future designs.

4-3 Flight Deck Design and Crew Complement; the near future

An understanding of cause and effect on crew size allows one to better understand the future design decisions. Flight crew size has been influenced by the state of supporting technologies, design philosophy, and political matters. Particular changes in crew size have been shown to be the result of redistribution of tasks; in later years, specifically to improve safety.

Future research might consider investigating task redistributions and human factors throughout (aviation) history. In such a way a model might be created to support future crew reconfigurations. A starting point to ordering the forms of task distribution in a clear structure, could be the following observations:

1. The first phase of FD design involved task redistribution largely within the confines of the FD; aircraft had to be self-sufficient and could not rely on external supporting systems.
2. During the next phase the tasks of the FD were distributed in such a way that reliance on external systems was possible, allowing alleviation of workload on-board and the removal of specific crew members.
3. In the second to last phase, innovations in on-board technology (automation) resulted in redistribution of tasks, so that two pilots could perform them all safely through interaction of on-board and external systems and persons (e.g. ATC and ILS).
4. Since the 1990's, commercial crew reduction has not yet moved beyond two. Innovations have however been taking place, allowing redistribution of tasks in future. Some examples are augmentation of Global Positioning System (GPS); greater computing power; digital data connections; and next generation ATM, soon allowing conflict-free pre-planning of routes in time and space.

Future developments may allow a redistribution of certain ATC tasks from ATC and the flight deck to automation. To better understand a reduction to single pilot, it may be worthwhile to create a model of the forms of task redistribution and enabling factors. When viewed from such a broader perspective, this may provide new insights into task distribution; and crew reduction.

4-4 Conclusion Evolution of the Flight Deck and Crew Complement

The optimal crew size depends on supporting technology, and human factors understanding, but also on the current perspective of the role of humans in the cockpit. Aviation stakeholders have not always agreed on optimal crew size. There have been several phases in FD design. Every crew reduction is synonymous to task redistribution. This can occur between humans or technology, either on-board or off, enabled by new technologies and/or new human factors insights. An important observation regarding automation and historical crew reductions, is that automation changes the relationships between people, and introduces new forms of error

(Dekker, 2002). Bureaucratic issues play a role in actual crew size, slowing innovation. As Decker highlights, more automation is not necessarily better (Dekker, 2002). Similarly, more information displayed in the cockpit is not necessarily safer. The same holds true for flight crews; more crew is not necessarily safer. To enable SPCO, it appears that the design of flight decks must enter a new era.

Chapter 5

FAA and EASA Regulations

This chapter examines the regulations relating to crew size of commercial aviation. The aim is two-fold; firstly, to narrow down the research question by identifying specifically which operations are not permitted single pilot. Secondly, to understand the reasoning why certain (civil) aviation operates with a single pilot, whereas others require a multi-pilot-crew. The question this chapter attempts to answer is:

> *What characterises flights that currently permit single crew operation, as opposed to flights requiring multi-crew operations?*

The approach is a three-step top down examination:

1. The mission statements of the International Civil Aviation Authority, the US Federal Aviation Administration, and the European Aviation Safety Authority are reviewed; to identify each organisation's purpose. In short, the agencies aim to minimize risk exposure to the public, both on-board and off-board, as a result of civil aviation. (See Section 5-1).

2. Keeping these mission statements in mind, the risk formula commonly applied in aviation safety theory (Rodrigues & Cusick, 2011), is used to derive factors driving total risk for any particular flight. The risk formula states the total risk is proportional to the sum of every event's likelihood multiplied by that event's damage. The risk formula is used for a qualitative analysis. (See Section 5-2).

3. Thirdly, the regulations were examined to identify which parameters dictate the minimum legal crew size. Based on the logic of the risk formula, it is assumed the FAR require multi-pilot flight crews on flights with greater risk, in order to mitigate some of this risk. The factors that dictate minimum legal crew size are compared to the risk drivers found before; those based on the risk formula analysis (See Section 5-3)

This approach has allowed the author to uncover some important issues. Not all of these issues are entirely new, though interesting nonetheless. These issues are relevant to the certification (and therefore design), of any future single pilot aircraft and flight decks. Limited manpower was available for this research. The results should therefore be considered as a general guide. Keeping this limitation in mind, the examination has yielded some interesting findings.

Verified is that aircraft mass, and somewhat crudely the type of operations, determine whether or not single pilot operations are permitted. Only small aircraft are permitted to be operated commercially with a single pilot. The aviation regulations have been found to be highly complex; based on assumptions dating back to 1965 (McClellan, 2006); lagging behind current innovations (BAE, 2012); and high in uncertainty. The effect is discouraging to innovation in single pilot operations.

Section 5-1 states the missions of the FAA, EASA, and ICAO. Section 5-2 characterizes the risk drivers associated with an arbitrary flight. Section 5-3 presents which parameters dictate whether single pilot operations are permitted. This section also makes a comparison of the risk drivers, and those adhered by FAA to specify minimum crew size. Certain shortcomings are mentioned in Section 5-4. Current regulations are undergoing changes, described in Section 5-5. The conclusions to this chapter are given in Section 5-6.

5-1 FAA, EASA, and ICAO Mission Statements

A quick introduction to the regulations is in order. In a nutshell, based on the mission statements of the ICAO, FAA and EASA, their mission is to protect public safety and public interest in civil aviation, and to guarantee safe, efficient, and environmentally responsible civil aviation (ICAO, 2012), (FAA, 2012c), (EASA, 2012). The agencies approach this by means of regulations and advisories relating to the four facets of airworthiness; aircraft type certification, maintenance, operating procedures, and training. The researched regulatory frameworks are assumed to accurately represent the aviation regulations of interest for this research.

5-2 Derivation of Factors that Drive Total Flight Risk

To itemize the characteristics of any flight that drive the flight risk level, the risk formula (Eq. (5-1)) has been applied in a qualitative manner. The risk formula states the total risk is proportional to the sum of every event's likelihood multiplied by that event's damage. Based purely on aviation and aerospace understanding, factors affecting probability and cost of damage have been listed.

$$Total\ Risk \sim (Probability\ of\ damage * Cost\ of\ damage) \tag{5-1}$$

The main factors that influence the probability of a damage event are:

- Aircraft
  - Aircraft speed. Faster speeds imply there is less time to observe, think, and act.

  - Number and type of engines. More engines reduce the probability of total simultaneous engine failure.
  - Avionics equipment; on-board and on-route.
  - Duration aircraft has been in-service. Greater likelihood for failures (and thus accidents) exists during the first and final years of service of an aircraft.
  - Adequacy of maintenance performed.

- Crew
  - Training (e.g. Visual Flight Rules (VFR), Instrument Flight Rules (IFR), day-night).
  - Crew experience.
  - Number of pilots; for the purpose of redundancy in case of incapacitation.
- External
  - Weather conditions (Instrument Meteorological Conditions (IMC)/ Visual Meteorological Conditions (VMC)).
  - Route flown
    - Airspace congestion along route.
    - Presence of ATC.
    - Geography (e.g. hazardous terrain).
    - Availability of supportive avionics infrastructure (e.g. Nav aids).

The main factors that determine the cost of a damage event are:

- Characteristics of damage
  - Lives or property.
  - On-ground or on-board.
  - The degree to which damage is to the *public*, determines how much protection is required. The more *public* persons are, the less awareness they can have of risks, and the lesser freedom they have to avoid risk.
- Energy and coverage of impact
  - Aircraft size.
  - Aircraft velocity at impact.
  - Amount of fuel on-board during impact.
- Number of lives
  - Number of passengers and crew.
  - Number of persons on ground; flight route geography.

To translate these risk drivers into regulations to safeguard airworthiness, practical measures must be used. Practicality of enforcement limits the effectiveness of regulations. The following section explains which factors dictate whether single pilot operations are permitted according to existing regulations.

5-3 Parameters that Actually Dictate Minimum Legal Crew Size

With regard to SPCO, the FAR and EASA regulations do not deviate much. The structure is highly similar; part numbers correspond. This chapter will refer mainly to the FAR. Of the four facets of airworthiness, aircraft type certification and operations are most relevant to minimum crew size. Parts 23 and 25 concern aircraft certification, Parts 91, 119, 121, 125, and 135 concern operating procedures. Part 23 covers small aircraft, mostly general aviation. Part 25 covers the larger Transport Category aircraft, to which stricter regulations apply.

Only in rare instances may Transport Category aircraft be operated single-pilot. The smaller Part 23 aircraft may generally be type certified for single-pilot, as long as demonstrations show the workload is acceptable. The classification scheme that determines whether an aircraft type is Part 23 or Part 25 certifiable, largely determines whether single pilot operations are permitted at all with that aircraft. However, for actual single pilot operations, more requirements must be met, as governed by Parts, 119, 121, 125, and 135. The following paragraph explains the functioning of the regulations using Part 23 certification as an example. The regulations concerning operations and their relevance to single pilot flights are explained later. The specifics why Transport Category aircraft may not be operated by a single pilot are explained last. The following section explains the parameters that determine whether an aircraft is certifiable in Part 23 or must meet the more stringent requirements of Part 25.

The regulations aim to protect the public by minimizing the total damage, through ensuring initial and continued airworthiness. As was expected, this is achieved in practice by imposing stricter rules in situations where the probability or severity of accidents is greater (Rodrigues & Cusick, 2011). Standards exist for each aspect of airworthiness. Simplifying somewhat, the FAR require a multi-pilot crew for all small aircraft (Part 23) that have a Maximum Certificated Take-Off Weight (MTOW) (as per the Flight Manual (FM)) greater than 12,500 lbs, and/or a number of seats greater than 9 excluding the pilot and co-pilot seats. These limits are extended to 19,000 lbs and/or 19 seats for commuter aircraft. Furthermore, the minimum crew size can never be fewer than that prescribed by the manufacturer in the Aircraft Flight Manual (AFM). Commuter aircraft must meet some extra requirements to reduce the risk. Flights with potential for higher damage severity (e.g. more passengers on-board), are compensated by rules which lower the probability. For example, the commuter aircraft may carry more passengers with a single pilot, however they must be equipped with at least two (non-jet) engines. It appears this is because the probability of an accident is lower in case of an engine failure in a multi-engine aircraft. Also, the higher speed of jet-aircraft is likely the reason why these may not be certified in the commuter category.

The larger aircraft require stricter rules, because the energy involved in an accident would be greater (Goyer, 2012). The number of seats is used as a cut-off parameter between Parts 23 and 25. This is likely the case since the number of passengers on board is assumed to depend roughly on the number of seats. The number of seats is used for practical purposes, as this value is relatively fixed and thus more practical to verify and practically enforce. More passengers on board would imply an increased severity in case of an accident. Hence, when more passengers are on-board, more stringent rules apply.

The level of restrictiveness of regulations is also linked to the type of operations. The regulations appear to try to *measure* the degree to which passengers are *public* citizens. (Recall that the regulatory bodies aim to protect especially the public). The regulations attempt to apply stricter rules to operations of more *public* nature. Part 119 determines which of Parts 91, 121, 125, and 135 are in effect, based on the type of operations. The rules of Parts 135 and 121 are most restrictive; applying to *common-carriage* (*public* operations). According to US 14 CFR Part 119, *common-carriage* operations are not permitted single pilot. The FAA states that a *common carrier* is characterized by: "a holding out of a willingness, to transport persons or property, from place to place, for compensation". (FAA, 2012d). To clarify, the FAA provides an example of a carrier that is *for-hire*, as having 24 contracts, compared to a *not-for-hire* carrier, having three current contracts. These regulations are confusing because the boundaries between a *common-carrier* and *private-carrier* are not explicit. To a number of operations, such as student instruction and crop dusting, Part 119 does not apply. For these operations, listed in Appendix C, single pilot operations are permitted, so long as not forbidden elsewhere in the regulations, such as in aircraft type certification.

It has been found that the commercial operations currently permitted single-pilot, are nearly exclusively general aviation. The FAA regulations do not permit other SPCO. A reason for this may be that the probability of single pilot incapacitation is too high. More precisely, the FAR state that during one flight, "the occurrence of any failure condition which would prevent the continued safe flight and landing of the airplane", must be *extremely improbable*; on the order of 1x10-9 or less (14CFR25.1309-1A) (NTSB, 2006, p. 89), (FAA, 2012d). Chapter 7 of this report shows the incapacitation rate of airline pilots to be roughly 5e-7 per hour. Thus, even in a flight of just one hour, pilot redundancy is required such that the continued safe flight and landing of the airplane is possible. Thus, it is the fail-safe design concept of Part 25 Transport Category aircraft systems certification, where a single pilot does not fulfil the requirements.

The pilot incapacitation rate does fall within the bounds defined by 14CFR25.1309-1A (FAA, 2012d) as being *improbable*; on the order of 1x10-5 or less, but greater than on the order of 1x10-9 per flight. It is a requirement that any failure condition which would "reduce the capability of the airplane or ability of the crew to cope with adverse operating conditions", to be *improbable* (NTSB, 2006). Hence, any form of redundancy of the pilot tasks other than a second pilot, according to current regulations of Part 25, would not be required to cope with adverse operating conditions. This is an important statement in relation to SPCO, particularly in relation to the design of backup systems in case of pilot incapacitation.

The FAA definition of adverse operating conditions are "A set of environmental or operational circumstances applicable to the airplane, combined with a failure or other emergency situation that results in a significant increase in normal flight crew workload". (14 CFR 23.1309-1 E) (FAA, 2012d). It should be noted that the above FAA definition refers to failure condition, whereas an incapacitation is more similar to a failed component. Further study should delve into incapacitation rates as failure conditions. That depth is outside of the scope of this research.

The parameters that should drive crew size (based on risk analysis using the risk formula), can be compared to the actual parameters that dictate minimum crew size according to the FAR. Risk depends on some factors that are not included in the FAA and EASA regulations in specifying minimum crew size. Factors that could be included are the characteristics of individual flights. Risks associated with a particular route may be sufficiently constant to be incorporated in the determination whether single pilot operations are permitted. Regulations specify minimum crew based on MTOW and the degree to which the operations affect the public. Limitations result from practical difficulties regarding the enforceability of rules. In today's world, with ubiquitous information technology and instant communications, perhaps a shift can soon be made towards flight-specific regulations; depending more on the characteristics of individual flights and routes, than the *one-size-fits-all* formulation that has served the previous decades.

This section explained in short which parameters actually dictate whether single pilot operations are legal. A number of shortcomings of the regulations have been identified. These shortcomings are discussed in the next section.

5-4 Shortcomings of Regulations

Whether the intention of protecting certain passengers more than others is justified, and practical, is debatable. Engineering ethics would argue that persons who are unaware of risks need more protection. But in this day and age, do common carrier passengers truly have less freedom of choice, and less awareness of risks taken than non-common carrier passengers? If different levels of protection are no longer justified, this is another reason to update the regulations. Whether the case or not, if the rules cannot be formulated in a clear and explicit manner, perhaps an alternative solution should be sought.

As mentioned, in this day and age, the view that certain persons require less protection than others should be re-evaluated. Access to information is now ubiquitous. The difficulty encountered in defining the regulations is apparent in the ambiguous terminology and virtual distinctions (e.g. between charter and scheduled airlines; when in essence these operations are very similar). Perhaps these vague definitions are a remnant from the age prior to deregulation of the airways, and an instance of the complications of politics and policy making (Doganis, 2010). Aviation legislation is largely a system of case-law (Larsen, Gillick, & Sweeney, 2012). That is, current legislation is based on all previous judicial court decisions throughout history, rather than adapting with time to current needs of aviation.

The risk formula is widely accepted, however the application requires that fundamental assumptions hold true. Some underlying assumptions on which FAR (and EASA regulations) are based, no longer hold true today. There is recent frustration in industry concerning the complexities of certification of small aircraft (McClellan, 2011). A study by Aircraft Owners and Pilot Association (AOPA) in 2011 resulted in a recommendation that Part 23 was due for an overhaul (AOPA, 2009). In 2009 the AOPA Director of Aircraft and Environmental affairs, Leisha Bell, stated,

> "While the existing approach has produced safe airplanes for decades, technological advances have changed the original assumptions of the Part 23 divisions" (AOPA, 2009), (Bell, 2009).

The issue is summarised as follows. Recent years have seen an increase in VLJs due to the advances in small turbine technology. The crash of a VLJ can be quite severe due to high speeds, and could be more likely due to the complexities and higher speeds (due to the time-risk relationship). Yet, the complex, high-performance VLJs, fall within the weight and seating bounds of Part 23 small aircraft type certification. To accommodate for these advances over the decades, Part 23 of the FAR has been incrementally updated; becoming more stringent to accommodate the higher risk aircraft.

The result is that Part 23 became overly complex. Certification of the intended simple lightweight aircraft became disproportionately expensive. At the time of the creation of Parts 23 and 25, the assumption that heavier aircraft are faster was justified. Today, this is no longer necessarily the case, but the regulations remain structured to differentiate risk based on MTOW. This example shows that (some of) the assumptions on which the regulations are based are no longer valid, with the result that regulations do not optimally fulfil their purpose; to ensure the safety and efficiency of civil aviation for stakeholders and the public. For this reason, a major overhaul of Part 23 has begun mid-2011 to bring it up-to-date. Earl Lawrence, manager of the FAA Small Aircraft Directorate, explains in an interview that the new Part 23 regulations are aimed at changing the current industry philosophy of *designing to requirement*, into *designing for effect* (Brown, 2012). The purpose of the overhaul is to remove the current barrier to innovation, reducing small aircraft product costs by half, whilst improving safety levels by 50%.

The last and final example of regulations being unclear particularly when it comes to single pilot operations, involves the design and certification of the Lear 23. This example is an indication of the cloudiness of the regulations, and the uncertainty with which industry must cope. Even experienced aircraft manufacturers cannot be sure which regulations will be required, and thus whether single pilot operations are acceptable. The Lear 23 was designed specifically to meet the requirements for Part 23 for the purpose of being certified for single-pilot operation; MTOW was limited at 12,500 lb by Learjet. However, the FAA created a special exception, requiring two pilots for this aircraft at the last stage of certification even though it is certificated under Part 23.

This chapter has argued that some of the underlying regulatory assumptions are out-dated. Technological advances have resulted in complex-high performance aircraft, to which the regulations are not adept. The author aims to illustrate that existing regulations should not be used as a strict recipe to determine whether single pilot aircraft, or any new concepts for that matter, are safe. Crew size should be a design consideration that depends on the relevant human factors. The fact that regulations are not fault-free was indicated by the controversial 80,000 lb rule, described in Section 4-2. The 80,000 lb rule is an example of the existence of inappropriate regulations, slowness to corrective change, and the adherence to incorrect assumptions.

This section has argued that the current FAA aviation regulations are out-dated. This more or less means the EASA regulations, which are highly similar, contain the same issues. Fortunately, the regulations are entering a period of change. This is the topic of the following section.

5-5 Period of Change

The overhaul for Part 23, starting mid-2011 and lasting about 18 months, will be completed soon. Parts 23 and 25 are based on old assumptions. It might be that Part 25 will receive an overhaul within 5 years. Further technological developments have been made, and more are expected. These changes continue to impact the effectiveness of current regulations.

Further developments are occurring in the realm of civil Unmanned Aerial Systems (UAS). Both in the UK, the EU, the US, and through ICAO Standards and Recommended Practices (SARPs), these regulations are being rapidly updated (FAA, 2012b), (ICAO, 2011). These are all indicators of change occurring within the greater aviation system. The impact of these changes on single-pilot operations will become clear in time. Even though EASA became fully functional only very recently (2008), these regulations too might demonstrate similar issues to the FAR's. The structure is very similar, and both are based on ICAO standards and recommendations. The EASA regulations have not been researched as in-depth as the FAA in this study.

What we are seeing appear to be hints that the general structure of the aviation regulations is out-dated. Human factors is an important field of research and design, with a huge impact on safety (See Chapter 6). Orlady implied the importance of human factors when stating in 1999; "human factors has become multi-disciplinary and requires special and very broad qualifications" (Orlady & Orlady, 1999, p. 55). However, the structure of regulations is not based on human factors issues, but still on aircraft weight. It is only since the late 1970's that human factors have been accepted throughout aviation industry (Wiener, Kanki, & Helmreich, 1993). The fact that the structure of regulations dates back to 1965 is evidence that human factors understanding has not been the driver of the overall structure. Yet, the overall structure has been shown to determine whether rules are stringent or lenient.

A clear rationale behind the form of the regulations could not be easily located by the author. The regulations themselves do not explicitly state the reasons opposing single-pilot operations of all large aircraft, or of small commercial aircraft. Although reasons opposing SP operations are not stated, some significant findings have been made in the examination of the FAA and EASA aviation regulations. The minimum crew depends on the MTOW, the number of seats (excluding (co)pilot(s)), and the type of operation. The regulations appear to have been drafted using the risk formula. But, the risk formula has been applied to assumptions that were correct at the time, yet today are no longer strictly true.

It is not easy to certify innovative designs at present. According to EASA, in reference to variations of rules across member states, "provision should also be made for reaching an equivalent safety level by other means" (EASA, 2008). Although this is stated, and historical examples of such provisions exist, this involves costly procedures (capital and time). A good example is the case of the Boeing 737; designed for two crew even though three was the norm at the time (See Section 4-1). Hence, although new systems with equivalent safety levels can be certified, in practice the costs are so high that designers are driven to minimize changes compared to existing systems. The more extensive the design innovation, the more attention it will receive during certification, and the more costly to realize. The regulations in their current form are an incentive to stick with tried and proven designs. They are an incentive against innovation (Goyer, 2012), and against single pilot commercial flight deck research.

5-6 Conclusions Regulations

This chapter has described the current state of regulations with respect to SPCO. The aim has been twofold; to identify when single pilot operations are permitted, and to identify technical hurdles to SPCO.

It turns out that single pilot operations of sizable aircraft are rarely permitted. Similarly, operations of more than a slight commercial tint, are not permitted to be operated by a single pilot. The main drivers to determine whether single pilot operations are permitted, are aircraft weight, seating capacity, and the degree to which the operation can be considered *commercial*. Yet, the regulations are not written in a clear and explicit manner. This leads to ambiguities in interpretation, and uncertainty in the certification process.

In this chapter, the risk formula has been used to itemize risk drivers of an arbitrary flight, which were then compared to the parameters determining whether or not single pilot operations are permitted. The parameters dictating whether SPCO are permitted, are somewhat different from the flight risk drivers. The differences appear to be the result of the faulty regulatory assumption that heavier aircraft are by definition more risky.

The regulations were originally structured to impose more restrictive regulations to heavier aircraft. Amendments in recent years to accommodate changes have been aimed at specific aircraft, rather than updating the structure of the regulations. The result is a complicated set of regulations; complicating certification and driving up cost, especially for more innovative designs.

The regulations impose more stringent requirements on operations of more civilian nature. It has been argued that the justification of this is questionable. The implementation is unpractical; resulting in rules that are ambiguous and contradicting. Fortunately, the regulations are in a period of change. It is expected these changes will affect the legality of single pilot operations, as well as the feasibility to certify innovative designs such as single pilot concepts.

This paper does not argue for or against SPCO. However, a finding is that current regulations are ill-suited for the certification of single pilot commercial concepts. It appears that the regulations are based on the assumption that redundancy in case of pilot incapacitation can only be ensured by means of a second pilot on board. With the current rapid development of UAS technologies, the regulations should be prepared for certification of such innovative concepts as alternative methods of ensuring pilot redundancy, for the event that such a newly designed concept might indeed meet the required safety standards.

The regulations themselves do not provide technical reasoning for two crew designs. It seems that an assumption is made that two crew is necessarily safer than one. As previous sections have shown, the assumption that more crew is safer, is not necessarily valid, just as more automation and more information in the cockpit are not necessarily safer. Crew size should depend on human factors issues, and should be the result of optimal design considerations; evolving within the changing work environments in aviation. The impact of human factors on SPCO is the topic of the succeeding chapter. This concludes Part 1A, in which the current state of SPCO was presented. Part 1B leads on to illustrate the technical challenges preventing the crew reduction to SPCO.

Part 1B

Single Pilot Commercial Operations: The Technical Challenges

Chapter 6

Human Factors Challenges

This chapter presents human factors as a major technical hurdle to single pilot operations. In current flight decks, challenging situations occur primarily in flight stages where workload is high, and/or when non-normal conditions occur. In the complex, highly automated flight decks of today, the pilots are challenged to the limits of human cognition, to maintain sufficient situational awareness. Human Factors are a major consideration in aircraft design, to ensure ease of operation and maintenance is within human limits (Rodrigues & Cusick, 2011). This chapter aims to answer the question:

> *What are the tasks of the commercial flight crew, and why can these tasks not be performed by one pilot?*

A triadic relationship in flight deck human interface design will be outlined. This design relationship exists between SA, WL, and automation. Performance monitoring by a human team member is illustrated to be an invaluable component of the aviation safety net preventing accidents.

Section 6-1 will explain the triadic relationship between SA, WL, and automation, within human interface design of the flight deck. Section 6-2 shall focus particularly on issues causing high work load. Section 6-3 shall look at why it is a challenge for two pilots to maintain sufficient situational awareness. Performance monitoring and other human factors hurdles to single pilot operations are discussed in Section 6-4. Potential ways to overcome these human factors hurdles to single pilot operations are discussed in the final section of this chapter, Section 6-5.

6-1 Situational Awareness, Workload, and Automation; Design Relationship within the Flight Deck

Since the 1970's, the significance of human factors to safety has been accepted throughout the aviation sector. The challenge for two-crew FD design today, is to ensure adequate situational awareness at an optimal workload, allowing safe and efficient operations at congested airspaces, whilst ensuring pilots remain in the loop with automation. Failure modes are anticipated in the flight deck design stage and integrated into flight deck procedures. The result is a flight deck where warnings and alerts are common; making optimal alert threshold design a topic much researched (Parasuraman & Wickens, 2008), (Parasuraman, 1987), (R.Parasuraman & O.Olofinboba, 1997), (C. Wickens & Colcombe, 2007), (C. D. Wickens et al., 2009). Although automated alerts to dangerous situations (such as collision warnings) can increase crew SA, too many false alerts will increase WL, and reduce trust in automation, causing complacency and even negatively impacting SA as alerts are ignored.

A further factor related to SA, WL, and automation, is the usage of checklists. Checklists have a history as being sources of error. In researching a single pilot variant of the Line Operations Safety Audit (LOSA), Earl identified that checklists were missed on several occasions. Deutsch also identified checklists as a source of issues for SPCO (Deutsch & Pew, 2005). WL reduction through automation of checklists is not an option; it would create more possibilities for failures, requiring more checklists. And yet, missed items within checklists remain a cause of accidents (Degani & Wiener, 1993), (Deutsch & Pew, 2005), (Turner & Huntley Jr, 1991). A trade off exists between more and less automation; captured by so-called ironies and fallacies of automation.

Automation can be used to reduce the workload of the pilot, but can introduce errors which are difficult for the pilot to recognise and identify. Autopilot mode switches requested by the Flight Management System (FMS), are an example of an action of the automation going unnoticed by flight crew. This can result in the pilot no longer being in the loop. The result can be that pilot and automation work against each other, leading to distraction and in worst case, collision. It is possible for the automation to alert the pilot of more of its actions. But this would increase pilot workload, potentially causing the pilot to miss more important information. Hence, the degree of autonomy is a design choice that affects WL and SA, and inevitably safety.

Current flight deck design aims to find the optimal level of automation, whereby crew has sufficient SA at WL that is just right. Boeing and Airbus take a different general stance; Airbus applies compensation automatically, whereas the Boeing approach aims to never bypass the crew (Rodrigues & Cusick, 2011, p. 168). Much avionics research is aimed at improving WL and SA, either through new displays, or through top down analysis of the tasks in the flight deck. Measuring WL remains a challenge, and new designs always create opportunities for new error forms.

The primary functions of the flight deck performed by flight crews are: “flight management, communications management, systems management, and task management” (Abbott & Rogers, 1993, p. 67). Flight management includes aviating (primary control) and navigating. Communications includes those with ATC, with other crew members, and any other forms. Systems management is the interaction (monitoring and management) of systems to perform particular functions. According to Schutte, “it is the job of the flight crew to merge these procedures together in a safe and efficient manner” (Schutte & Trujillo, 1996).

For a detailed description of the split of tasks between pilot flying and pilot not flying using Cognitive Task Analysis (CTA), the reader is referred to Deutsch, (Deutsch & Pew, 2005). Previous work of Deutsch is aimed at modelling performance of aircrews and air traffic controllers. According to Deutsch,

> "In meeting their responsibilities, the captain and first officer have a significant number of tasks in process, each of which requires a coordinated mix of perceptual, cognitive, and motor skills. The scenarios create situations in which the response to demands must be prioritized to achieve acceptable performance". (Deutsch & Pew, 2005).

During high workload, pilots prioritize tasks and allocate resources through a variety of scheduling methods (Schutte & Trujillo, 1996). Segal and Wickens identified shedding of secondary tasks as a coping strategy during high workload (Segal & Wickens, 1990). A common resulting issue is the failure to reschedule low-priority tasks (Goteman & Dekker, 2002). Thus, a clear triadic relationship exists between workload, situational awareness and automation.

6-2 High Work Load

In current flight decks, crew workload is excessively high during peak workload. Peak workload occurs during approach through busy air spaces, especially IFR, weather, turbulence and unplanned IMC, in combination with faults, warnings and alerts. Miscommunication is a common factor. In extreme non-normal conditions, the WL can become too high even for two pilots to perform all tasks. Such situations can lead to accidents; it is a fact that most accidents occur at flight phases where the workload is the highest (Orlady & Orlady, 1999, Fig. 2.5). In reference to LOSAs, Earl found that, "Generally, LOSAs show that descent, approach and landing phase has a proportionately larger number of errors due to high workload at this time" (Earl, Murray, & Bates, 2011). FAA and other institutions expect a double in air traffic in 2025 compared to 2005 (EMBRAER, 2012), (Airbus, 2012), (Gomes, 2012). This implies workload will become more of an issue in future.

Lawhon has summarised the safety issues related to (GA) single pilot IFR flights,

> "Very simply, the problem is pilot workload, aggravated by the need for multi-tasking. A single IFR pilot also serves as navigator, radio operator, systems manager, onboard meteorologist, record keeper, and sometimes, flight attendant. En route flight in benign weather is usually not too stressful, but add high-density traffic in poor weather conditions or a significant equipment malfunction, and overload may not be far away" (Lawhon, 2006).

Small turbojet aircraft certified for single pilot operations require certain alterations to the cockpit, aimed at allowing the single pilot to take on the tasks usually performed by a team of two. The requirements are a number of extra components or flight deck functions. Canadian regulations for operation of Cessna Normal Category (Part 23) models 501 and 551 single pilot require installation of the following equipment: an autopilot with approach coupling capability; a flight director; a boom microphone; and a transponder ident button on the pilot's control wheel (TransportCanada, 1997). These requirements aim to enable a redistribution of all routine tasks to a single pilot, in a very practical manner; allowing him to perform certain tasks in parallel, whilst retaining more heads-up time. For SPCO of more complex aircraft that routinely operate in busy airspaces, peak workload especially during non-normal conditions should be the focus of design alterations to the flight deck.

6-3 Inadequate Situational Awareness

As said, WL and SA play an important role in aviation safety. Endsley states, “having high level of SA can be seen as perhaps the most important aspect for achieving successful performance in aviation” (Endsley, 1999). An unidentified lack of SA by even a single crew member can have significant effects on safety. ICON Consulting provide a list of factors most influential on maintaining a shared mental model (Anderson, Embrey, & Hodgkinson, 2001). This section outlines the major challenges situational awareness poses for SPCO. SA according to Endsley is,

> “the perception of elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future” (Endsley, 1999).

Endsley identifies three levels at which SA occurs: perception, explanation, and prediction. A study of accidents of major US air carriers over a four year period found 88% of accidents caused by human error to be due to SA problems (Endsley, 1999). Problems on the perception level of SA (monitoring) accounted for 72% of SA problems. This suggests that monitoring would be an even greater human factors issue for SPCO.

The automation of monitoring is attempted through electronic warning display systems, but these systems have shortcomings. Problems are of perceptual nature, such as overload of auditory and visual alerts (Mårtensson & Singer, 1998, p. 41), and cognitive nature, such as misinterpreting the alerts (Ulfvengren, Mårtensson, & Singer, 2002). Wickens researched the cost of pilot attention with different forms of information communication, finding that redundancy (audio and visual) is not always better considering workload. Sound is shown to interfere with task performance (Farmer, 2002). Goteman emphasises the importance of scientific research into call-outs and alerts, pilot behavior, and WL (Goteman & Dekker, 2002). Prioritization of alerts remains an issue, as overloaded pilots are known to (dangerously) disregard warnings in order to focus on flying. This is an example of task shedding, mentioned before. The *alarm problem* (Woods, 1995), and distractive effects of cockpit alerting systems (Pritchett, 2001) are well known human factors issues. The chosen alert threshold is again an example of a trade-off between SA and WL, involving pilot trust and complacency. Ulfvengren studied pilots’ preference and performance with various degrees of automation; finding that providing the pilot with highly filtered and processed data allowed for pilots to process the information; resulting in better performance. Higher levels of automation do however risk pilot complacency.

Commercial aircrews must maintain situational awareness whilst dealing with complex automation. In many cases automation can reduce the cognitive WL of the pilot. However, the automation surprise is a common resulting issue. As Borst illustrates,

> “automation only partly involves pilots in the cognitive work, which can decrease the SA that would be needed to enable pilots to appropriately reason and reflect on situations unanticipated by the automation” (Borst, 2009), (Bainbridge, 1983).

For example, FMS opacity can reduce SA, creating the potential for causing errors (Feary et al., 2010). According to Sebok, “State changes in FMS are not salient; [and] may go unnoticed by pilots" (Sebok et al., 2012). The so called fallacies of automation, and ironies of automation (Lee, 2008), illustrate the contradictory impact of the level of autonomy of systems.

For SPCO, SA presents a serious design challenge. Commonly in complex sociotechnical systems, system autonomy is increased to alleviate the human operator of workload, allowing him more time to maintain an accurate mental model of the current situation. But as explained, higher levels of automation challenge the pilot in maintaining sufficient SA. SA remains extremely important so that the crew can take control in case of situations unanticipated by the automation. Adaptive automation, which adapts to the pilot WL, is discussed later as a potential means to overcome WL and SA challenges for SPCO.

6-4 Performance Monitoring and other Human Factors challenges

Performance Monitoring (PM) of the Pilot Flying (PF) may be the most important contribution to safety by the Pilot Not Flying (PNF). Monitoring, cross-checking, and challenging are essential roles of the PNF (Burian, 2007). Such monitoring can be a significant barrier preventing accidents. Performance Monitoring includes; alertness for hypoxia symptoms; reviewing decisions and actions; a reduction in the opportunity for visual, somatogravic and other (as of yet unknown) illusions (Orlady & Orlady, 1999, p. 83). Cultural factors can jeopardize Performance Monitoring (such as in case of an inappropriate Trans-Cockpit Authority Gradient (TCAG), also known as power distance). An unsuitable TCAG can lead to failure to take corrective action of one's superior. The importance of PM is illustrated through the historical occurrence of disproportionately high accident rates in cockpit cultures where the power distance was too high or too low (Sohn, 1993), (Helmreich, 1994).

The monitoring of performance is optimized through Crew Resource Management (CRM). CRM trains crew to maximize performance (safety and efficiency) through utilization and management of all resources available (hardware, software, and live-ware), especially to maximize the performance monitoring aspect of the "total team concept in aircraft operations" (Orlady & Orlady, 1999, p. 119). Single Pilot Resource Management (SRM) contributes to safety of instruction flights and other single pilot general aviation operations; where the single pilot must make the most effective use of all resources at his/her disposal. The FAA refers to Single Pilot Resource Management with the acronym SRM (FAA, 2010). SRM is not yet sufficiently developed for SP operation of large commercial aircraft. Clearly, the SRM would depend on the resources available to the single pilot, and thus would depend on the work environment of the single pilot; SRM procedures and training should be an integral constituent of the development of a SPCO flight deck. What is certain, is that "pilots operating as single pilots need to be able to critique their own performance" (Halleran, 2010).

Fatigue and stress remain important issues; disturbed biological rhythms and related sleep disturbance and sleep deprivation are common problems for many career pilots. Alfred states,

> "While sleep loss is a key stressor degrading cognitive performance and mood, other operational stressors, including heat, cold, high altitude and dehydration, substantially contribute to what, in aggregate, is a devastating level of impairment in all cognitive functions assessed, including vigilance, reaction time, working memory, and reasoning" (Alfred et al., 2010).

Powell researched fatigue amongst line operations of 3 to 12 hours. Factors identified to affect level of fatigue are mostly; the time of day; length of duty; number of sectors flown; whether flying to or away from home-base (Powell, Spencer, Holland, & Petrie, 2008). Single pilot crew scheduling should consider these factors.

Well-established roles of captain and first officer, as well as pilot-flying and pilot-not-flying, are vulnerable to sequences of errors leading to incidents and accidents (Deutsch & Pew, 2005). Deutsch found important vulnerabilities to single pilot operations to be; checklist events, problem-solving tunnels (tunnel vision), biasing of decisions, missing knowledge, errors of omission, communication in challenging situations, unacknowledged situational alerts, and the time-risk relationship. Deutsch recommends a "more deliberate top down approach" to establish a philosophy, policies, and procedures for single pilot commercial aircraft operations.

This chapter has demonstrated the prominence of human factors challenges to SPCO. It appears current flight deck designs have achieved all that is possible with incremental innovations. A more radical innovation seems appropriate to overcome the WL and SA issues and further improve safety. Recurring challenges and problems arise with current flight-deck designs. Due to these issues, the workload remains high and errors are prone. Thus, current flight decks are not suited for SPCO.

AOPA sums up the situation for small turboprops and jets certified for single pilot operations,

> "the statistics appear to confirm the notion that single-pilot operations create higher workloads and greater demands on pilot skill when the chips are down and stress levels run high" (Horne, 2008).

Landing is most dangerous, followed by IFR approach. Landing gear is a major cause of accidents for single pilot turboprops and jets (Horne, 2008). Though these statements on behalf of AOPA refer to single piloted GA; they might indicate that SP operations in general should not be underestimated.

6-5 Potential Solutions to Human Factors Challenges

This section provides potential solutions to the human factors issues challenging SPCO. The main issues identified are; performance monitoring; high workload during approach in non-normal conditions; and insufficient situational awareness within complex flight decks.

On SP certified small aircraft, the boom microphone and transponder ident switch on the yoke allow a single pilot to perform all routine tasks. A potential similar adjustment to the flight deck of large aircraft is the Heads Up Display (HUD). HUDs allows the pilot to maintain outside visual whilst observing primary flight information. HUDs have been available on commercial aircraft since the 1970s, mostly to reduce the acceptable minima for take-off and landing in the vicinity of terrain and in poor visibility. HUDs are likely a necessary but not sufficient flight deck requierment for SPCO. Synthetic Vision Displays (SVD) may provide improved terrain, weather and other information to increase SA especially in poor visual conditions. Currently verbal communications remain one of the weakest links in aviation (Rodrigues & Cusick, 2011). In future, combined visual and auditory communications will be enabled through new digital data links. Interaction between aircraft within the air transport system might allow a new phase of flight deck design, whereby the optimal role of pilots might change.

Previous reductions in crew size are enabled by a redistribution of tasks, such as among ATC. Air Traffic Control Officers (ATCOs) however, are under increasingly high workload. Innovations in ATM will allow ahead-of-time 4 dimensional conflict-free trajectory planning (Klomp et al., n.d.). SESAR and System Wide Information Management (SWIM) are expected to enable such 4D trajectory planning in Europe, relieving ATCOs and pilots of workload during approach. New decision support aids may support pilots in decision making (Ekström, Flügel, Wilkinson, & Patchett, 2002). A design tool for automation of the flightdeck for NextGen has been created by Sebok, aiming to make FMS designs more intuitive (Sebok et al., 2012). A reallocation of separation assurance to some means of automation, could be achieved through in-trail separation using ADS-B (Dimitrakiev, Nikolova, & Tenekedjiev, 2010).

Adaptive Automation (AA) can provide additional benefits in balancing workload and maintaining the user's situational awareness. More research is required to identify when adaptation should be user controlled or system driven. AA could reduce the workload when operators are overloaded; boosting SA at times when workload is again low; by returning the crew attention to tasks previously automated (Parasuraman, Sheridan, & Wickens, 2008). Thus, AA could provide a solution to task shedding. For more details regarding OFS and AA, please see Chapter 8.

As stated, Single Pilot Resource Management (SRM) is aimed at helping single pilots identify resources, analyse information, and make decisions (Summers, Ayers, Connolly, & Robertson, 2007). Salas provides a comprehensive summary of the evolution of CRM (Salas, Wilson, Burke, & Bowers, 2002). CRM plays a fundamental role in maintaining safety within multi-crew and single pilot operations. The relationship between time and risk is particularly relevant to single pilot operations. For a summary of decision making for single pilot (helicopter) operations, the reader is referred to (EHST, 2012). Although concerning helicopter operations, many of the issues are common to fixed wing aviation. An adjustment of Line Operations Safety Audit (LOSA), has made this auditing method applicable to Single Pilot Line Operations Safety Audit (LOSA:SP) (Earl et al., 2011). Though the sample size was too small for statistical analysis, Earl demonstrated the feasibility of LOSA:SP. A finding was that single pilots who verbalize their intentions, as if in multi-pilot operations, seem more attentive in cross-checking and had fewer mismanaged procedural errors (Earl et al., 2011). The findings from LOSA:SP audits can be used to further develop SRM. SRM could and must play a role in the design of any SPCO.

In military aircraft design, solutions to high workload (e.g. due to sensor complexity), are commonly; an extra crew member or decision support aids to lower WL and increase SA (Ekström et al., 2002). Essential is to provide the right information at the right time and way, avoiding information overload. Among lessons learnt from military aircraft, is that two set of eyes are better than one, if and only if a corresponding picture is seen (Penrice, 2000). Therefore, in the case of single pilot commercial operations, if support is to be provided by an off-board co-pilot, shared cognition will be very important. The information available to the off-board (human) support would be limited due to communication bandwidth constraints. Research regarding team performance and shared cognition may provide new design insights for SPCO. There has been an increase in research into teams and shared cognition in recent years (Salas, Cooke, & Rosen, 2008). The reader is referred to Sulistyawati, Chui, and Wickens

(Sulistyawati, Wickens, & Chui, 2009) for further reading. In any future SPCO, specialists of shared cognition and teams should be involved in the design process.

6-6 Conclusion Human Factors and SPCO

Human factors have been shown to pose a design challenge for SPCO. The various issues in multi-crew flight decks mostly involve insufficient situational awareness or a workload that is too high. These issues are most problematic when non-normal conditions arise. In fact, non-normal conditions are often attributable to these human factors problems. Workload and situational awareness play a role in the many (multi-crew) aviation accidents. If SPCO are to become a reality, these issues must be overcome. The interested reader is referred to (Lee, 2008), in which Lee has reviewed 71 papers published over 50 years on the topic of human factors and automation.

Once the human factors issues are resolved, tasks might be redistributable to enable safe operations with a single on-board pilot. Such redistribution should ensure sufficient heads up time, to aviate and navigate, whilst communications and other tasks are also taken care of. Some alternative method of performance monitoring should be implemented on any future SPCO's. Performance monitoring remains a key challenge to be overcome, before SPCO can be realized. The following chapter explains the fourth major technical hurdle to SPCO; the hazard of pilot incapacitation.

Chapter 7

Single Pilot Incapacitation

A major safety argument in support of multi-pilot crews is redundancy in case of incapacitation. Incapacitation of the pilot due to a medical event is a real concern in single pilot operations. The redundancy offered by two pilots ensures that the required civil aviation safety levels are met. The frequency of occurrence of incapacitation of a single pilot is too high to meet the safety target levels required of aircraft, within the greater aviation system.

The degree to which a pilot medical event is a safety threat to conventional aircraft operations depends on; the frequency at which an event is likely to occur; the severity and type of symptoms; rate of onset of symptoms; and the duration of symptoms. Medical events that are difficult to reliably identify by a monitoring system form a greater hurdle to single pilot operations. Heart issues are the most common form of incapacitation, followed by psychological events.

This chapter summarizes prior incapacitation research. Section 7-1 describes the various forms of pilot illness that could result in an incapacitated pilot, and the severity of each. Section 7-2 quantifies the incapacitation rates, based on recent research, and compares the risk to other failure modes. Section 7-3 discusses the potential for ensuring redundancy by setting more stringent constraints on pilot age and medical screening. Section 7-4 describes the state of the art of identifying incapacitations by means of automated monitoring. For a detailed research of functional requirements for a Single Pilot Incapacitation Redundancy (SPIR) solution, the reader is referred to Part 2.

7-1 Forms of Medical Events that Could Result in an Incapacitated Pilot

Cockpits in current airliners are not designed with the intention of routine operation by a single crew member. As indicated, the workload can become too great, and the situational awareness can be insufficient. However, current multi-crew cockpits have been designed such that in case of an incapacitation of either pilot, the remaining pilot can physically reach all essential controls, for a degraded completion of the mission. For routine operations however, current aircraft designs require two pilots to meet target safety levels. This section examines the various forms of incapacitation that could threaten safety in SPCO.

A second crew member in the cockpit offers redundancy in case one should fall ill, mentally or physically, and be unable to land the aircraft safely. A distinction is made between two forms of pilot medical unfitness to perform flight tasks while on duty. The most recent and comprehensive research has been performed by Evans (Evans & Radcliffe, 2012). Evans makes a distinction between impairment and incapacitation. In case of impairment, the pilot is unfit to fly the aircraft temporarily; not resulting in an accident, were the aircraft to be single-piloted. Evans researched medical events of all UK airline pilots during 2004; events occurring whilst on and off-duty. Based on thorough research of every event, an informed judgement was made; would this medical event have resulted in loss of control of the aircraft if it occurred during single pilot operation? If so, the event is considered an incapacitation. Naturally, incapacitations are the main focus of this research regarding SPCO.

The precise definitions Evans adheres are the following. An impairment, is "a partial incapacitation associated with symptoms that resulted, or would have had the propensity to result, in a reduction of function or distraction from the flight crew task" (Evans & Radcliffe, 2012). The definition for incapacitation was chosen with "single-pilot operation in mind; incapacitation would result in loss of aircraft, if single pilot" (Evans & Radcliffe, 2012). A third form of unfitness was researched by Evans; the occurrence of temporary unfitness to perform flight duty due to accidental injury, pregnancy, or medical condition. The causes are included in Table 7-1 for the reader to gain a more complete understanding of those factors affecting pilot fitness to fly. The causes of temporary unfitness are not equivalent to the causes of incapacitation, as Table 7-2 portrays.

The distribution of incapacitation types appears to be dissimilar for those occurring in-flight, and those occurring off-duty. The results of Evans' study are,

> "In 2004 there were 16,145 UK/JAR professional pilot license holders. Of the notified medical events, 36 presented as incapacitations; half were cardiac or cerebrovascular. In-flight incapacitations were predominantly of psychiatric cause. There were four sudden deaths. The type of incapacitation varied with age. A male pilot in his 60s had 5 times the risk of incapacitation of a male pilot in his 40s. The annual incapacitation rate was 40/16,145 = 0.25%." (Evans & Radcliffe, 2012).

The most common incapacitation forms, based on those notified collectively whilst in-flight and off-duty, are of cardiac or cerebrovascular nature (cardiovascular causes). Evans findings that such incapacitations represent roughly half of all notified incapacitations (Evans & Radcliffe, 2012), are in agreement with earlier research by the ATSB (Newman, 2007) and DeJohn (DeJohn, Wolbrink, & Larcher, 2006). Cardiovascular incapacitations are most likely to result in fatal accidents in conventional aircraft designs. Although Evans, DeJohn, and the ATSB agree on cardiovascular incapacitations being the cause of roughly half of incapacitations, Evans found that in-flight incapacitations were "predominantly of psychiatric cause" (Evans & Radcliffe, 2012).

The fact that proportionally more psychiatric incapacitations were notified whilst on flight duty, could mean a number of things:

Table 7-1: Causes of episodes of temporary unfitness among UK commercial pilots in 2004. (Evans & Radcliffe, 2012, p. 44)

System Category	Number	Percentage
Accidents	131	18
Pregnancy related	24	3
Cardiovascular	103	14
Cerebrovascular	8	1
Dermatologic	3	<1
Diabetes	8	1
Ear, Nose, and Throat	46	6
Endocrine	5	<1
Gastrointestinal	59	8
Genitourinary	30	4
Hematologic	2	<1
Infectious disease	9	1
Information not received	5	<1
Miscellaneous	12	2
Musculoskeletal	126	18
Neurologic	21	3
Neoplasms	25	3
Ophthalmologic	17	2
Psychiatric	71	10
Respiratory	15	2
Total	**720**	**100**

1. Firstly, these proportionally higher rates of psychiatric incapacitations in-flight might be an indication of the high psychological pressures exerted on (some) pilots whilst on duty.

2. Alternatively, these differing rates might be an indication that some pilots who experienced a psychological incapacitation whilst off-duty (in the examined time-frame) did not report (or even recognize) the incident or any symptoms leading up to the incident. This would be a serious issue, as for the purpose of safety, "under UK Air Navigation Order, there is a statutory responsibility on a pilot not to fly if he is unfit" (Evans & Radcliffe, 2012). Evans does state that "the main difficulty is in obtaining data for incapacitations that occur outside the working environment" (Evans & Radcliffe, 2012, p. 42). It is possible that pilots might see an incentive not to report such events, as it might lead to withdrawal of their commercial pilot license. It is not the purpose of the author to make allegations, yet the author does wish to consider all possible causes of the discrepancy between off-duty on on-duty psychiatric natured incapacitations. The root of the discrepancy should be a topic of further study by specialists trained in aviation psychology; to better understand the psychological pressures on the pilots while on-duty, and/or to benefit aeromedical and psychiatric screening by educating pilots on recognizing psychological threats to their fitness to fly; both have the potential to benefit aviation safety.

3. A third explanation for the discrepancy between the cause of those incapacitations that occurred whilst in-flight and while off-duty exists. The size of the sample of incapacitation event could be too small to determine the proportion of incapacitation causes with sufficient certainty (statistical significance). This seems to be a plausible reason, as only

Table 7-2: Pilot incapacitation among UK commercial pilots in 2004 (This table excludes 4 sudden deaths that occurred). (Evans & Radcliffe, 2012, p. 45)

Cause of Incapacitation	Number of events	Ages of pilots
Cardiovascular		
Acute myocardial infarction	6	39, 52, 54, 58, 59, 64
Chest pain	2	48, 60
Arrhythmia	3	42, 50, 66
Pulmonary embolus	2	45*, 49
Cerebrovascular		
Stroke	4	33, 42, 50, 59
Subarachnoid hemorrhage	1	48
Other		
Panic attack	3	34*′, 35*′, 64*
Spontaneous pneumothorax	4	30, 40, 44, 62
Gastric ulcer	1	47
Perforated appendix	1	24
Syncope	1	54
Bowel obstruction	1	48
Biliary colic	1	51*
Migraine	1	47
Prolapsed intervertebral disc	1	52
Epilepsy	2	24, 55
Vestibular disturbance	1	39*
Spontaneous abortion	1	40
Total	**36**	

* Occurred in flight or in the simulator.

5 of the total of 40 incapacitations occurred in-flight or in the simulator. Furthermore, two of the pannick attacks occurred to the same pilot within a 6 month period. Hence, the data may not illustrate the true statistical properties of the risk of incapacitation.

4. A fourth explanation for the higher rate of psychiatric incapacitations while in-flight exists. Possibly, cardiac health issues are easier to screen for because symptoms are more pronounced and are present over a longer period of time. Pilots at risk for cardiovascular incapacitation are then deemed unfit to fly before an incapacitation can take place. Because psychiatric incapacitations are accompanied by less prominent symptoms, this makes it more difficult to identify a pilot at risk before an incapacitation occurs. It could be so that cardiovascular incapacitations are accompanied with symptoms that, in comparison to symptoms leading up to psychological incapacitations such as pannick attacks are; a. more easily noticed by the pilots themselves (who then seek medical help); or, b. symptoms that build up more gradually over time, allowing the symptoms to be observed in the standard aeromedical screening.

Further research is justified to determine the reasons for the difference between rate of cardiovascular and psychiatric incapacitation occurring in-flight and off-duty. As explained above, the difference hints at some interesting characteristics that, when better understood, could benefit aviation safety through more targeted aeromedical screening. Some potential causes identified are; the increased psychological pressure while in-flight; the inability or weak incentive for psychologically unstable pilots to report psychiatric incapacitations that occur while off-duty; possible statistical insignificance of the incapacitations measured in-flight; and the increased difficulty in screening for psychiatric incapacitation risk before such an event can take place.

Based only on the incapacitations that occurred inflight, psychiatric illness and acute gastrointestinal illness (food poisoning) are the most common forms of incapacitation. The threat of food poisoning might be mitigated with consistent eating habits prior to flight duty. Neurological issues are a more minor cause of incapacitations. Subtle incapacitation by (prescription or other) drug abuse is pointed out as a substantial risk by Besco (Besco, 1990). The risks alcohol and drug abuse pose to SPCO require further research.

An introduction to the physical environment and the physiology of flight is provided by (Orlady & Orlady, 1999). Medical risks particular to the aviation environment are hypoxia and hyperventilation. The Time for Useful Consciousness (TUC) of hypoxia is as little as 40 seconds. TUC is “the time in which a person can be expected to take effective preventive measures” (Orlady & Orlady, 1999). The extremely short TUC makes hypoxia a serious safety concern for both multi-crew and single pilot operations. Hypoxia also threatens multi-crews because decompression would affect the entire flight crew simultaneously. Solutions in modern aircraft include an automatic emergency descent initiated if an un-acted upon cabin depressurization is sensed (Kaminski-Morrow, 2009). The acceptance of such autonomous emergency descent modes by pilots are an issue of trust.

In recent years there has been a risk of blinding by ground based laser light. An FAA study over a five year period ending 2008, found an increasing trend in percentage of aircraft laser illuminations below 2000 feet. This potentially represents an “escalating threat to aviation safety” (Nakagawara, Montgomery, & Wood, 2010).

The Australian Transport Safety Bureau (ATSB), identified the two main incapacitation causes of Australian civil pilots (not exclusively, but including airline pilots), to be acute gastrointestinal illness (21%), and exposure to toxic smoke and fumes (mostly carbon monoxide) (Newman, 2007). These findings are based on all civil pilots in Australia. The findings of Evans and Houston, however, are based exclusively on commercial airline pilots, which is a subset of all civil pilots. Possibly for this reason, toxic smoke and fumes are found as the main cause by the ATSB report; smaller aircraft are likely included in the statistics, in which the engines are closer to the cockpit. This or other factors, might increase the risk of incapacitation due to toxic smoke and fumes in small aircraft. Further research is needed to identify if this is indeed the source of the difference in findings between ATSB and Evans.

The basic human need for periodic urination presents practical, but also, safety concerns. It is currently unacceptable that no pilot is at the controls at any moment in flight. However, an overfull bladder can severely degrade human cognitive performance. Reports of private single pilots in dire need for a toilet in-flight exist to illustrate this. An overly full bladder can distract single pilots from tasks. Such a physiological state, combined with challenging flight conditions, could be the figurative straw that breaks the camel’s back; with serious consequences. As a solution, procedures and emergency apparatus might be installed, within reach of the single pilot's seat. For short flights, this apparatus would provide merely a precautionary emergency measure. For long-haul single pilot flights, a second shift of aircrew on-board would mean toilets breaks are possible using normal cabin toilets. For medium duration flights, the single pilot would either have to use the emergency apparatus, or leave the seat; which is currently unheard of. Thus, urination is a banal human need, but can potentially form a serious safety threat. The design of routine procedures as well as emergency apparatus are an ergonomics challenge; both male and female pilots would need to agree that the emergency solution is acceptable. Thus, this seemingly banal issue, could become a significant barrier to SPCO.

Research by Evans has identified a strong *healthy worker effect* among the more than 40,000 UK airline pilots in 2004. The healthy worker effect implies that of any population, the subset of the population that works tends to live a healthier lifestyle than the total population. There indeed is a lower prevalence of smoking among UK airline pilots, than the average UK population (Evans & Radcliffe, 2012), (De Stavola et al., 2012). Although pilots are more frequently overweight, they are less frequently obese. Similarly, Houston's research confirms such a higher rate of regular physical exercise also exists among US airline pilots (Houston, Mitchell, & Evans, 2011).

7-2 Quantification of Incapacitation Rates

The hurdle incapacitation poses to SPCO can be quantified. The most recent and comprehensive research is that of Evans. Evans calculated the incapacitation rate based on medical incapacitation events that occurred either on and off-duty, to establish a base-line minimum risk level[1]. This minimum risk level allows the most secure risk analysis. 40 Incapacitation events occurred among the 16,145 UK/JAR professional pilot license holders in 2004 (Evans & Radcliffe, 2012). These incapacitations include those occurring whilst on flight duty, and whilst off-duty. The annual incapacitation rate is 40/16,145 = 0.25% per pilot annually, occurring whilst on or off-duty. With roughly 8760 hours in a year, this amounts to 2.83e-7 incapacitations per hour, or 0.0283 per 100,000 (flight) hours. Amongst US airline pilots, from 1993 till 1998, a rate of 0.045 incapacitations per 100,000 flight hours occurred (DeJohn et al., 2006). This corresponds to a rate of 4.5e-7 incapacitations per flight hour. Rates in the US and UK are clearly of very similar magnitude.

Let us compare the actual incapacitation rates, to the rates required to satisfy overall aviation safety levels. The UK incapacitation rate of 0.25% per pilot annually, satisfies the maximum level of 1% per annum used by the UK Civil Aviation Authority (CAA), as a basis for risk assessment of commercial pilots undertaking multi-pilot operations (Evans & Radcliffe, 2012).

In the EU, quantification of safety levels is required in ATM as per ESARR4; requiring an "overall risk Target Level of Safety (TLS) for ATM of 1.55e-8 accidents for every flight hour" (Lundberg, 2002). The rates of 4.5e-7 in the US and 2.8e-7 in the UK for incapacitation alone,

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[1] NOTE: Evans states "In seeking to ascertain a minimum incapacitation rate, only definite incapacitations were included. The classification of incapacitations and impairments was deliberately strict to ensure that the medical event rates derived were 'minimum' ones and did not overplay the incidence of events" (Evans & Radcliffe, 2012).

are above the safety threshold for overall ATM risk. Hence, multiple pilots are a necessity to meet the TLS for ATM in the EU. This is of course a somewhat crude and limited analysis.

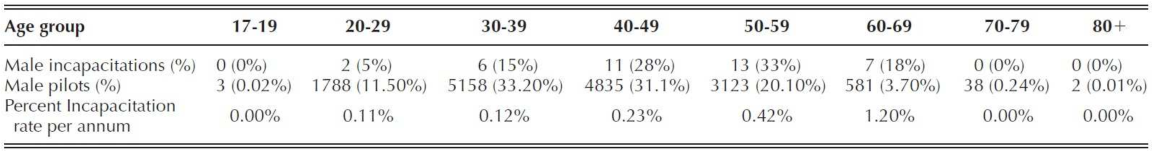
Similarly, the Federal Aviation Regulations (FAR) state that the occurrence of any failure condition, that would prevent the continued safe flight and landing of an airplane, to have a probability on the order of 1e-9 or less (NTSB, 2006, p. 89). This probability is defined per flight; from the moment the wheel blocks are removed until the complete standstill of the aircraft. For flights of one hour, the requirement would thus be that a single pilot incapacitation occurs less frequently than 1e-9 per hour. The rates found by Evans and DeJohn (2.8e-7 and 4.5e-7 respectively) are two orders of magnitude greater than is acceptable by the FAR for any failure condition of equivalent consequence. The FAA assigns maximum probabilities to failure conditions, yet an incapacitation is more similar to a component failure. Thus the comparison is not 100% sound. However, two orders of magnitude are a clear indication that a single pilot does not meet the requirements of the FAA, unless redundancy is provided by some other means. Alternative forms of incapacitation redundancy are the topic of Part 2.

7-3 Incapacitation Risk Mitigation by means of Single Pilot Age Restrictions

The previous section has shown that a lone pilot does not satisfy aviation target safety levels. Two pilots, on the other hand, might provide an excess of redundancy. More research would be required to verify this, considering all possible failure conditions of an aircraft. This section scratches the surface of potential alternative methods for achieving similar safety levels, without a second on-board pilot but by means of more restrictive constraints on pilot age.

Historically, pilot age has been used as a parameter to control combined incapacitation risk of two pilots. Evans identified a greater incapacitation risk for pilots towards the older age groups. Male pilots in their 60's have a risk of incapacitation that is five times as high as male pilots in their 40's (Evans & Radcliffe, 2012). The spread of male pilot incapacitation with age is presented in Table 7-3. Pilots' proneness to medical events (rendering them temporarily unfit to exercise the privileges of their license) also shows this relation to pilot age, as illustrated in Figure 7-1.

Table 7-3: Annual male incapacitation rates by age group. (Evans & Radcliffe, 2012, p. 47)



Age group	17-19	20-29	30-39	40-49	50-59	60-69	70-79	80+
Male incapacitations (%)	0 (0%)	2 (5%)	6 (15%)	11 (28%)	13 (33%)	7 (18%)	0 (0%)	0 (0%)
Male pilots (%)	3 (0.02%)	1788 (11.50%)	5158 (33.20%)	4835 (31.1%)	3123 (20.10%)	581 (3.70%)	38 (0.24%)	2 (0.01%)
Percent Incapacitation rate per annum	0.00%	0.11%	0.12%	0.23%	0.42%	1.20%	0.00%	0.00%

However, pilots of age generally have more flight experience. Furthermore, a simulator based study of single pilots under IFR found that experienced pilots showed a lower workload than novice, or recently inactive pilots (Rinoie & Honda, 2000-6.7.3). Thus more aged pilots have a higher risk of incapacitation, but make valuable contributions to flight safety.

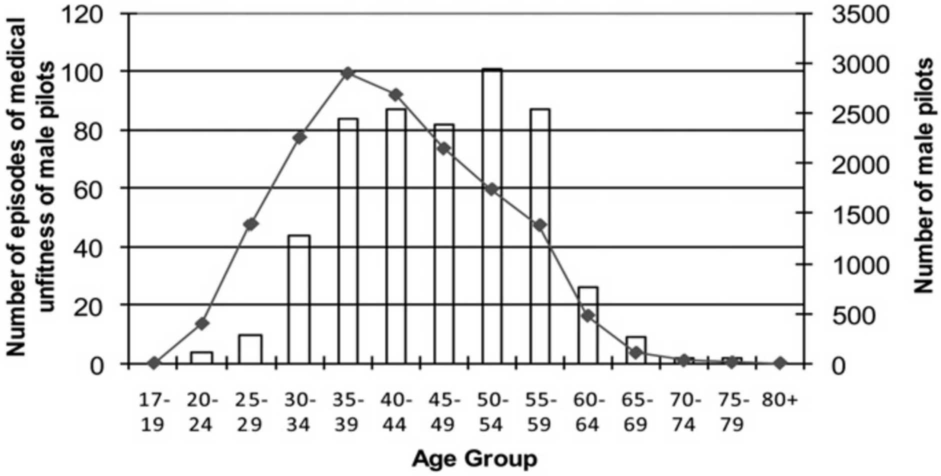


Figure 7-1: Comparison of medical causes of unfitness of male pilots by age with the male pilot age distribution. Bars show number of unfit episodes; black diamonds show number of male pilots. (Evans & Radcliffe, 2012, p. 45)

It has been the topic of discussion whether pilots should be forced to retire at the age of 60, to maximize safety. In 2006, ICAO adjusted its recommendation for Part 121 (Scheduled airlines). Until November 23rd 2006, pilots were forced to retire from commercial operations at age 60. ICAO now advises, that in commercial operations requiring multi-pilot crew, at least one pilot must be fewer than 60 years of age; the other must be less than 65 years of age. Pilots between 60 and 65 years of age require a medical examination every six months (FAA, 2007). The findings of Evans support this rule change. The ICAO rule change is an advisory standard; implying that member states may impose different age limits on domestic flights, but must accept international operations abiding by the ICAO standards, to use airspace and airports. By allowing airline pilots to operate multi-pilot commercial operations until age 65, the incapacitation safety levels are met, and the experience of aged pilots is used to benefit safety. This example illustrates how safety targets can be met in alternative ways.

Similarly, one might consider more stringent medical screening of single pilot crews. According to Evans, “the incapacitation rate of single pilot operations should be on the order of 10 times less likely than for multi-pilot operations, i.e., 0.1%” (Evans & Radcliffe, 2012). Evans’ study demonstrated the actual rate is closer to 0.25%. 0.1% is achievable only in the youngest of pilots; and yet, older pilots have greater flight experience. Evans suggests an age limit for SPCO of 60 years, with an increased concentration of screening on pilots over 50 years of age. The significance of incapacitation as a hurdle to SPCO is emphasised by the ATSB. A study of the accident and incident database of the ATSB over 31 years (from 1975 to 2006), identified 98 pilot incapacitation events (Newman, 2007). Of the 16 resulting in accidents, 10 accidents resulted in fatalities; all of which were single-pilot operations. This illustrates the significance of pilot incapacitation, to the safety of single pilot operations.

Alternative form of redundancy, to complete the aviation mission with degraded performance, would be a necessity to ensure safe SPCO. The completion of the mission with degraded, yet acceptable performance, would imply landing the aircraft at a nearby airport. During this landing, separation with other airspace users and terrain must be ensured. The exact distinction between mission completion with degraded performance and mission failure, are beyond the scope of this research. The exact distinction does impact which is the optimal form of redundancy. Some possible forms of redundancy are; automated landing; landing by off-board pilot using remote control; or landing by cabin crew trained in operating the FMS and other autopilot functionality then available. To be clear, redesigns of conventional flight decks are required for any of these forms of redundancy to be feasible.

Security in case of distributed control as well as incapacitation identification, present multidisciplinary technical challenges. Some examples of specific relevant research are included in the following chapter. The development of potential Concepts of Operations (ConOps), are a suggestion for future work. Pilot health monitoring for incapacitation detection and safe landing whilst maintaining separation, are major incapacitation-related challenges to SPCO.

7-4 Identification of Incapacitation

In order for other forms of redundancy to be feasible, an incapacitation must be identifiable at some minimum level of reliability. Pilots will not accept working with automation that has the authority to remove them from the loop, unless the reliability has been proven. In such cases, the reliability must be extremely high, and pilots must have the authority for manual override. Trust is a fragile element making up part of the relationship between pilots and automation. The identification of psychological incapacitations is a major technical challenge to SPCO.

Evans' findings are that most incapacitations that occur in-flight, are of psychological form (Evans & Radcliffe, 2012) (see Section 7-2). These incapacitations appear to be extremely difficult to identify in-flight by an autonomous monitoring system. The actions of a pilot suffering a psychological incapacitation may be difficult to distinguish from a pilot responding to an unusual (and unanticipated) situation. In such case, the pilot would also give unusual (unanticipated) commands, in an attempt to resolve an unanticipated hazardous situation. Since unanticipated situations are the precise reason human pilots are required on-board, in every case when such a situation needs to be resolved, the pilot actions might be recognised as strange behaviour. This strange behaviour might be falsely identified as incapacitation. If ordinary, (anticipated) actions could resolve any situation; the pilot would not be necessary. By this logic, in all unanticipated situations whereby the pilot must perform unusual actions, the pilot could be recognised as being psychologically incapacitated; causing the automation to take over control of the aircraft. That would render the pilot powerless to resolve the unanticipated situation.

Incorrect identification of incapacitation would be most detrimental to safety during safety critical phases of flight, and during already problematic (unanticipated) situations. Automation can only protect against anticipated situations. Hence, functionality must exist for the pilot to take back control from the aircraft. A false identification of incapacitation and subsequent initiation of an auto-landing during normal conditions, would result in unnecessary delays and other costs, but would pose a lesser threat to safety than a failure of automation to identify and act on an actual incapacitation (as long as the pilot can either manually override, or the automated landing and separation functionality is extremely reliable). If the ability exists for the single pilot to take back control of the aircraft, this may prevent costs and delays. It should not be possible however, for single pilots to disable the incapacitation identification monitor completely.

Similarly, a human remotely observing the state and actions of a single pilot, might incorrectly consider the pilot psychologically unfit. Psychological screening might be intensified through allocation of more resources or more frequent screening. This might allow identification of psychological issues prior to manifesting in-flight. This goes beyond the scope of this research. Based on these difficulties, incapacitation of psychological nature is considered a major technical hurdle to single pilot operations.

Fortunately, accidents that involve deliberate disregard of standard procedures are rare (Rodrigues & Cusick, 2011, p. 156). Hence, it is assumed that two pilots are not required for ensuring the best intentions of pilots.

Of the incapacitations occurring while on and off-duty combined, half are heart-related issues. Cardiac arrests and other heart issues could be identified through in-flight health monitoring of the pilot. Automation of landing has been technically possible for over 30 years. Autonomous separation assurance would be more challenging (BAE, 2012). An automated solution should be feasible, to land single piloted aircraft, should the pilot be incapacitated by a cardiovascular medical event. In many forms of incapacitation events, the pilot (or cabin crew) might be able to identify the medical event; initiating some form of emergency automation mode.

Current multi-crew, long-haul, cargo flights with crews operating in shifts should be first candidates to any SPCO. These flights might be operable single pilot for the cruise flight phase over unpopulated regions, allowing other pilots to rest. (Section 6-2 described accident rates as being greatest in flight phases with the highest workload). During non-cruise flight phases, and in case of unusual situations, the resting single pilot could return to the flight deck immediately. This is in contradiction to interest shown by low-cost carriers; suggesting single pilot operation of short flights (Charette, 2010). The greatest risk of accidents occurs during take-off, approach and landing. Thus, short flights are at much higher risk per unit time of flight. Furthermore, per unit time of flight, short flights are more likely to cross congested airspace, and over densely populated regions. The sub-research on regulations found parameters such as route geography to impact total flight risk (see Section 5-2). Initial single pilot commercial flights are suggested to be operated on long-haul routes, during the cruise flight phase only. The second shift of (single pilot) flight crew on-board, would enable a multi-pilot crew during the more taxing and higher risk portions of the flight, and in case of non-normal conditions. It should be noted that aviation safety remains a matter of probability; it will not be possible to eliminate accidents altogether. Even on long-haul flights operated with modern airliners, sometimes a three-man flight crew may not be sufficient to guarantee the safety of a flight with a modern airliner. An example was flight AF447; an A330-203 flying from Galeao International Airport in Rio de Janeiro to Charles de Gaulle International Airport, Paris. Flight AF447 was crewed by a captain and two co-pilots, and yet upon failure of the autopilot and speed indicators, the airplane's flight path could not be brought under control by the two co-pilots, or the captain, who joined later (BEA, 2011).

This section has explained that the greatest challenge to providing incapacitation redundancy by alternative means is the reliable identification of incapacitation. Identification of psychological incapacitations (roughly half of all incapacitations occurring in-flight) pose a great challenge. Cardiovascular incapacitations (accounting for roughly half of all incapacitations occurring inflight or off-duty combined) are much lesser of a challenge to identify using technology available today due to the relation to heart rate measurements. Section 8-3 on measurement of Operator Functional State (OFS) and Adaptive Automation (AA) explains why. Based on the findings regarding pilot redundancy, the cruise phase of long-haul (cargo) flights over scarcely populated regions are suggested as initial SPCO, should these ever come to be.

7-5 Conclusions Incapacitation

This chapter reviewed literature research regarding pilot incapacitation. It has been found that two pilots are a requirement in order to achieve target aviation safety levels. Current airline pilot incapacitation rates are approximately 4e-7 per flight hour in the US and UK. The most common incapacitation forms are psychological and cardiovascular. Alternative forms of redundancy may allow a redistribution of tasks to one on-board pilot and supporting technologies. A major technical hurdle is the identification of psychological incapacitations by means of an automated monitoring system. Cardiovascular incapacitations are much more feasible to identify reliably, as will be explained in the following chapter. Some design considerations for alternative forms of redundancy have been discussed shortly. The following chapter shortly delves into some technologies identified during this research. These technologies might help overcome the identified technical hurdles to SPCO. Part 2 defines the functions required of incapacitation redundancy solutions for SPCO, and how these might be provided.

Chapter 8

Developments with Potential to Overcome the Technical Hurdles to SPCO

The previous chapters have examined the factors that resulted in the current multi-pilot commercial aircrew convention. The main technical hurdles were identified to be high workload, low situational awareness, the absence of performance monitoring by an on-board human pilot, and incapacitation. This chapter looks at current developments that may aid in overcoming these technical hurdles. Particularly, this chapter crudely aims to answer the question:

> *How might new technologies help overcome the identified technical hurdles to SPCO in future?*

Section 8-1 summarises the Autonomous Systems Technology Related Airborne Evaluation (ASTRAEA) project. Section 8-2 reviews developments relating to future ATM projects; SESAR in the EU, and NEXTgen in the US. Section 8-3 reviews the current state of the art of measuring Operator Functional State (OFS) and Adaptive Automation (AA) and support. Section 8-4 looks at the possibility of digital communications of aircraft health data and the possibility of remote control. Conclusions to this chapter are provided in Section 8-5.

8-1 Autonomous Systems Technology Related Airborne Evaluation & Assessment (ASTRAEA)

ASTRAEA is a collaborative project working to integrate civil use of UAS in non-segregated airspace. To achieve this, industry, the CAA, and academia have been working together since 2004. ASTRAEA is relevant to SPCO because the technical and non-technical challenges are very similar. The main issues identified by ASTRAEA are those of legality, safety, and security (BAE, 2012). ASTRAEA aims to overcome these issues by collaborative development of new certification processes and the development of new technologies aimed at:

- sense and avoid;
- autonomy;
- communications;
- operations;
- and human system interaction (BAE, 2012).

Many of the challenges of UAS are similar to the challenges of SPCO. In case of an incapacitated single pilot, the aircraft would be (at least temporarily) unmanned. Some potential solutions to safely land an aircraft in such a case are: some form of automation, the command by remote co-pilot, or command by less thoroughly trained cabin crew. This would require a number of the technologies such as sense and avoid, and increased autonomy in decision making. Therefore, potential solutions to create redundancy in case of incapacitation run into similar hurdles as integrating UAS in airspace. Apart from the issues of safety and security, there is also the issue of legality, as current certification procedures are not adept to such innovative solutions for incapacitation redundancy (see Chapter 5). Hence, the resulting developments from the ASTRAEA team could be beneficial to realizing SPCO. Unfortunately, more detailed information is difficult to come by, as technical reports are not made public at this stage.

If successful, the technological developments of ASTRAEA will not only aid to realize safe unmanned landing in case of incapacitation, but could also aid in the redistribution of routine tasks to help overcome the other technical hurdles to SPCO. These hurdles were identified to be the lack of situational awareness, excess workload, and non-existence of performance monitoring by an on-board co-pilot. By allocating tasks away from the pilot, it appears that the primary functions of the pilot would become even more monitoring oriented in comparison to that of management as is currently the case (see Section 6-1). Such a shift in functions of the pilot would require the rethinking of many factors relating to the pilot work, but occurring outside the specific time and place of the cockpit. For example, the pilot would need different and possibly more frequent training to overcome issues such as complacency and degradation of manual control abilities. The pilot would require a different set of skills and knowledge; possibly even a knowledge and understanding drawing nearer to that of a software and controls engineer, to identify failures within such a complex aircraft. The limited talent pool of candidates for such training might pose a challenge for realizing SPCO in this manner. Another possibility is that the new systems are so advanced, that the pilot's main tasks might be the repairing of failures (such as electrical fire) whilst the automation would continue to fly and land the aircraft in nearly every scenario. Such a distribution of tasks between human and automation would only be an option if the autonomy would be sufficiently robust to deal with all conceivable scenarios. Although history has shown that human designers cannot anticipate all possible scenarios, robustness only needs to exist to deal with sufficient scenarios such that the safety of the new system surpasses that of existing aircraft systems.

Visions of radical alternative future cockpit concepts may appear as fantasies to many engineers. And yet as this research has shown, current flight decks appear to have reached a stalemate, where new insights and innovations are required to achieve very significant advances (see Chapter 3). Fortunately, innovations are currently underway that could help to enter a new phase of flight deck design. These developments are the topic of the rest of this chapter; Section 8-2; Section 8-3; and Section 8-4. To achieve grand innovations, it may be necessary to step away from the tried and proven - but possibly limited - safety of conventional aviation systems. To do this, it can be very worthwhile to envision *sci-fi* scenarios of the far future. If nothing else, such visualization can help foresee unanticipated situations, benefiting development of even safer systems.

8-2 Nextgen ATM, SESAR, and Conflict-free Four Dimensional Trajectory planning

The increasing demands on ATM (ATCO workload, capacity, and efficiency) were outlined earlier. The SESAR (Europe), and NEXTgen (US) projects aim to upgrade the ATM systems to meet the increasing demands. The motivation for SESAR is to reduce delays within air transport. Together with digital data links and SWIM, 4D (space and time) trajectory planning will be possible in future (Klomp et al., n.d.). This could enable a number of flight deck innovations. Such innovations may help overcome high workload and low situational awareness in the flight deck.

4D trajectory planning and Tunnel in the sky displays may reallocate responsibility for separation assurance to automated ATC systems; increasing airspace capacity. Dwyer conducted a review of separation assurance and collision avoidance operational concepts for the next generation Air Transportation System (ATS) in 2009. At the time, Dwyer found that a form of supervisory control of separation by ATCOs appeared the most viable concept (Dwyer & Landry, 2009). Synthetic vision systems can increase SA by displaying weather, terrain, and other information (Borst, Suijkerbuijk, Mulder, & Van Paassen, 2006). Such modality can increase SA and reduce WL for single pilot operations.

A shift is taking place from auditory information communications (such as ATC traffic cueing) to visual. Using new display forms, digital data links can facilitate improved SA and WL. A somewhat recent similar innovation is the Cockpit Display of Traffic Info (CDTI) enabled by digital data link. Wickens warned that visual in-cockpit technology should be adopted with care for single pilot operations, as pilot attention is a limited resource challenged by technology (C. D. Wickens, Goh, Helleberg, Horrey, & Talleur, 2003). The use of visual (and textual) communications appears to be on the increase. Text based Controller Pilot Data Link Communications (CPDLC) technology will improve working memory and accuracy of general aviation single pilots (Romeoville, 2009).

8-3 Operator Functional State Measurement and Adaptive Automation

Adaptive Automation refers to the dynamic allocation of tasks to human and machine. Byrne defines adaptive automation as, “an approach to automation design where tasks are dynamically allocated between the human operator and computer systems” (Byrne & Parasuraman, 1996). Tasks are allocated based on strengths of the operator, optimal timing for tasks, and the psychophysiological state of the operator (Mulder, Dijksterhuis, Stuiver, & De Waard, 2009). A positive effect of AA can be the reminding of pilots of previously uncompleted tasks at a time when workload allows it, to bring SA back to required level (Parasuraman et al., 2008). Ideally the optimal timing for tasks can be determined by automation based on the Operator Functional State. According to the Research and Technical Organisation of NATO, Operator Functional State is defined as:

> “the multidimensional pattern of human psychophysiological condition that mediates performance in relation to physiological and psychological costs. OFS results from the synthesis of operator characteristics, current operator condition, and the operator’s interaction with operational requirements (NATO, 2004)”.

The current state of the art of OFS is not sufficiently developed for substantial AA applications within safety critical systems. However, current research may be sufficiently developed to reliably identify cardiovascular incapacitations, by means of unobtrusive sensors. The identification of incapacitations presents a significant technological challenge to realize single pilot commercial operations.

OFS can be measured based on either psychophysiological markers, or performance markers. During a large part of many civil flight operations, little active interaction between pilots and the automation takes place. Thus, much current research relating to adaptive automation in aerospace applications is aimed at identifying the OFS through measurement of psychophysiological markers. The concept of remotely monitoring humans in their natural environment existed as early as the 1960’s (Schwitzgebel & Bird, 1970). However, the application of AA based on OFS is not currently ready for implementation in civil aviation.

Hockey investigated two EEG (electroencephalography) ratios and HRV (Heart Rate Variability), as markers for strain (Hockey, Nickel, Roberts, & Roberts, 2009). Potential markers of mental effort are brain and autonomic measures. Brain, cardiac, and eye signals are relevant to accurately estimate OFS (Kaber et al., 2011). The exact markers tested are beyond the scope of this research. For further information, the reader is directed to aeromedical journals. The references suggested here provide an introduction to measurement of OFS. Measurement of OFS during experiments is highly obtrusive, in order to obtain high quality data for analysis (Mulder et al., 2009). In practice, in a flight deck work environment, measurements would have to occur in unobtrusive ways. A consistent result among research is that certain markers have been proven to be useful indicators of OFS, yet require much individual calibration. Current challenges are the many-to-many relationship between OFS and markers. Current research into OFS targets online (real-time) acquisition and analysis abilities, so that the adaptive automation loop can be closed (Hockey et al., 2009).

Fairclough reviewed the state of the art of physiological computing in 2009. Fairclough identified six fundamental issues for physiological computing systems; 1 complexity of physiological inference; 2 validating interference; 3 representing state of user; 4 explicit and implicit system interventions; 5 defining cybernetic loop; 6 ethical implications. Fairclough found the concluded that physiological measurement is at an early stage of development (Fairclough, 2011).

Hence, psychophysiological measurement is in the early stages. AA based on psychophysiological measurements is in an even earlier development stage. It is the view of the author that before adaptive automation depending on OFS can be applied in civil aviation, a period of data collecting in the actual work environment is required. During this time of learning, theories of inference can be validated. A less precise measurement of the vital signs might be used to identify incapacitations. Such identification would be useful for single pilot operations. In case of an incapacitation a warning might be provided to alert the pilot, and if no pilot response results, an automated landing initiated.

Incapacitations of cardiovascular nature should be the easiest form of incapacitation to identify with autonomous monitoring equipment. This observation is based on the fact that existing monitoring equipment for measuring OFS must distinguish between much more minute variations in pulse rates and shape than would occur in case of a heart attack (or other cardiovascular problems). Thus, it should be possible to reliably and unobtrusively identify cardiac arrest with today's technology. This might allow for redundancy against in-flight cardiac arrest of single pilots. Such incapacitations are shown to make up a significant proportion of incapacitations. Challenges may lie in ensuring reliability, considering the high electromagnetic noise environment of the cockpit, known to create EEG artefacts (Haarmann, Boucsein, & Schaefer, 2009).

Identification of psychological incapacitation is beyond the scope of this research. The current state of the art of measuring OFS appears limited to recognizing stress levels indicative of pilot workload. Psychological incapacitations cannot be reliably recognized by monitoring systems at this time. Psychological forms of in-flight incapacitation may need to be prevented and avoided by other means, such as more frequent medical screening.

Pilot fatigue can be monitored using systems such as the Electronic Pilot Activity and Alertness Monitor (EPAM). EPAM is able to monitor pilots to identify periods of sleep during flight. The Boeing 747-400 uses a similar system based on FMS input only (Cabon, Bourgeois-Bougrine, Mollard, Coblentz, & Speyer, 2003). During certain flight phases there is little interaction between pilot and FMS. Thus, more advanced monitoring that purely based on FMS input would be essential to enable SPCO. For necessary measures to manage risk due to fatigue, the reader is directed to Cabon, (Cabon et al., 2008). A survey of wearable sensor-based systems for health monitoring and prognosis has been performed in 2010 by Pantelopoulos. The purpose of these devices is the real-time feedback of individuals' health conditions. Pantelopoulos found,

> "Increasing healthcare costs, tech advances in miniature biosensing, smart textiles, microelectronics, and wireless communications, the continuous advance of wearable sensor-based systems will potentially transform the future of healthcare by enabling proactive personal healthcare and ubiquitous monitoring of a patient's health condition" (Pantelopoulos & Bourbakis, 2010).

An example device, LifeGuard, is a monitoring system capable of multi-parameter crew physiological observation. LifeGuard is tested for application in terrestrial and space environments. Acceptable accuracy and satellite transmission are proven. Pantelopoulos rated the state of the art of each system according to various parameters including; data encryption and security; operational lifetime; real-time application; computational storage and requirements; reliability; cost; inference robustness; and fault tolerance. It must be remembered that these systems are largely intended for continuous civilian use. For single pilot health monitoring, the design drivers would be somewhat different. The monitoring system should be unobtrusive. The feasibility is proven by the various publicly available systems, which can measure heart signals and breathing with wearable garments or sensors installed in seats. This would present a solution for identification of cardiovascular incapacitations. For details on specific health monitoring systems the reader is referred to Pantelopoulos; (Pantelopoulos & Bourbakis, 2010).

The aim of measuring OFS is to create automation that adapts to the needs of the operator. Byrne defines adaptive automation as,

> “an approach to automation design where tasks are dynamically allocated between the human operator and computer systems” (Byrne & Parasuraman, 1996).

The science of measuring OFS is in its infancy, thus AA applicable within civil aviation does not seem realistic within the decade. The research towards AA might however result in spin-off technologies allowing reliable and unobtrusive incapacitation identification.

8-4 Aircraft Health Monitoring and Remote Control

In the last decade, there have been a number of research projects directed at embedding sensors within Composite Fiber Re-enforced Plastic (CFRP) airframe structures, with the aim to monitor the structural health in real-time (Hunter et al., 2013), (Pattabhiraman, Gogu, Kim, Haftka, & Bes, 2012), (Staszewski, Boller, & Tomlinson, 2006), (Farrar & Lieven, 2007). Structural Health Monitoring (SHM) has the potential to improve the safety and reduce the maintenance costs of aerospace structures (Wu et al., 2010). One type of sensor used is the Fiber Bragg Grating (FBG) (Panopoulou, Loutas, Roulias, Fransen, & Kostopoulos, 2011), (Takahashi et al., 2010). Alternatively, Ihn demonstrated that “low frequency Lamb waves generated by PZT (Piezoelectric Lead Zirconate Titanate) transducers can successfully be employed to monitor in real time damage evolution in composite laminated structures” (Ihn & Chang, 2008). It is likely that such embedded sensory systems will allow more accurate monitoring and prediction of airworthiness, in real-time.

Dimanti provides a review of structural health monitoring techniques for composite structures (Ihn & Chang, 2008). One such concept described by Pattabhiraman, uses “on-board sensors and actuators to assess the current damage status of the airplane, [which] can be used as a tool to skip the structural airframe maintenance” (Pattabhiraman et al., 2012). Hunter et al developed a concept of operations at NASA; “an integrated system concept for vehicle health assurance that fully integrates ground-based inspection and repair information with in-flight measurement data for airframe, propulsion, and avionics subsystems” (Hunter et al., 2013). If hazardous subsystem states can be recognised before developing into a safety threats, this will allow the crew to act in time to mitigate the risk. Also, if fewer potential problems develop into serious incidents, this would result in a reduction in overall flight crew workload. Thus, real-time health monitoring systems (both structural and subsystem health) offer potential SA and WL benefits to the flight crew. As this report illustrated, WL and SA are two major technical challenges obstructing SPCO. Hence, the application of real-time (airframe and subsystem) health monitoring systems could bring SPCO closer to reality.

Similarly, the data recorded on the Digital Flight Data Recorder (DFDR) can be used to the same purpose. Safelander is a project that suggests the digital communication of the digital data, to monitor the health of aircraft remotely. Safelander proposes a system of remote control, whereby control can be taken over remotely, such as in case of incapacitation (Lennel, n.d.). For more information regarding Safelander, the reader is referred to (Lennel, n.d.). Security aspects regarding such remote takeover are beyond the scope of this research, but could bring greater safety threats than such a system solves.

8-5 Conclusion Current Developments with Potential to Overcome Technical hurdles to SPCO

This chapter has argued that similar safety levels as in current multi-pilot operations may be achieved by single crew flight decks designed specifically for that purpose. Harris supports this view, stating that “with the appropriate use of human factors methods it is possible to design and develop a single crew commercial aircraft using largely existing technology” (Harris, 2007).

It must be noted, that with the current growth in air transport demand, maintaining equivalent safety levels may not be sufficient, as in absolute sense the number of accidents would increase. The required safety levels must be more restrictive in future, to maintain the equivalent level of perceived trust by the public (Orlady & Orlady, 1999). For more technologies that might support single pilot operations the reader is referred to (Deutsch & Pew, 2005) and (BAE, 2012).

Deutsch suggests an approach to SPCO whereby “the pilot-not-flying tasks be taken over by automation that emulates current pilot-not-flying task execution” (Deutsch & Pew, 2005). Based on the findings in this report, such a one-to-one mapping of tasks as suggested by Deutsch in 2005 seems inappropriate. The aviation environment is in a period of change; any single pilot concepts should be designed to take advantage of innovations and consider human factors (Sharples et al., 2007). Simply replacing the pilot-not-flying with an automated agent hardly does so. In fact, linearly replacing the pilot-not-flying tasks with an automated agent neglects the essence of CSE, ignoring many lessons learnt about automation and human factors. The author suggests an approach to SPCO based on a top-down analysis of the flight deck, using appropriate CSE techniques.

Chapter 9

Conclusions Parts 1A and 1B

Part 1 of this thesis report has aimed to create a comprehensive list of the technical challenges that obstruct SPCO. To understand this broad topic, an extensive lateral research approach was taken. Topics that repeatedly turned up were researched in greater detail in relation to single pilot commercial flight operations. Other topics researched in detail, to understand the context, were the history of flight crew reductions, current regulations pertaining to SPCO, and trends in aviation. These topics have been covered in Part 1A.

A number of sub-research questions were presented in the introduction. The answers found can be shortly summarised. At this moment, regulations permit only light-weight aircraft and non common-carrier operations, per single pilot. Currently, Air Transportation Systems appear to have entered a period of change. ATM updates in Europe and North America, rapid passenger km growth in Asia and South America, and the preparation of regulations for integration of civil UAS are some examples of these changes. Because historical crew reductions are found to have been enabled by task redistribution made possible by new technologies and/or improvements in human factors understanding, the above described changes are expected to alter the playing ground for potential SPCO.

Part 1B presented the technical hurdles found to challenge single pilot aircraft designs. The challenges are; excessive workload; insufficient situational awareness; the replacement of peer performance monitoring; and ensuring incapacitation redundancy. Workload and situational awareness are particularly significant during approach through busy airspace and during non-normal conditions. The mentioned aviation trends including the realization of four dimensional trajectory planning may well help overcome the workload and situational awareness challenges. Incapacitation redundancy requires functionality for identification of incapacitations and for safely landing. Four dimensional trajectory planning could facilitate the latter; landing whilst maintaining separation. Similarly, two trends are expected to help overcome the hurdle of incapacitation identification; advancements in wearable health monitoring devices in the public sector; and research towards measurement of operator functional state for adaptive automation. If the workload, situational awareness, and incapacitation challenges are indeed overcome, that leaves pilot performance monitoring.

Performance monitoring by a second on-board, human pilot, is still commonly seen as the last safety net in accident prevention; removal of which would initiate discussions regarding fundamentals of automation design and the role of humans within complex sociotechnical systems. On the other hand, flights are performed today with single pilots in other areas of aviation, although fewer lives are at stake. A concept to support performance monitoring of the single pilot, might be the real-time remote monitoring of digital flight recorder data, including the monitoring of aircraft health as well as pilot performance. By monitoring digital flight recorder data autonomously and remotely unusual flight situations might be identified sooner. Flight crews could be remotely supported by specialists in a preventative fashion; even before problems become known to pilots. Referring to Reason's Swiss cheese accident causation model; potential accidents might then be identified before the holes line up. Currently, a number of holes can line up un-noticed by flight crews due to high workload and low situational awareness. Modern Flight data recorders record several thousands of parameters; far too much information for the flight crew to digest. The challenge in such a concept lies in the transmission of certain components of the data. A feasibility study of such a concept would be a valuable topic for future research. A primary goal of such research would be to identify which flight data to transmit for remote monitoring within the constraints of telecommunications infrastructure. Such a system for remote monitoring of aircraft health and crew performance could aid in overcoming the performance monitoring challenge for SPCO.

The future of Single Pilot Commercial Operations will be impacted by developments in ATM and Regulations. Consortium projects in collaboration with regulatory authorities such as ASTRAEA are a necessity to pave the road for highly innovative concepts such as SPCO. A limitation of the research of Parts 1A and 1B has been the limited manpower to research this topic. Yet, this research has managed to present a comprehensive report illustrating the technical challenges to SPCO, thereby providing a foundation for research towards potential single pilot concepts. These concepts should keep the hurdles of situational awareness, workload, incapacitation, and performance monitoring - presented in Parts 1A and 1B of this MSc thesis - in mind.

At this stage, it is aimed to research a particular area relating to SPCO in more detail. At present, SA and WL challenges are receiving ample research attention, quite possibly leading to improvements in the near future. Performance monitoring without a human co-pilot presents too broad a topic for a detailed study in the limited time remaining for this MSc thesis. During this research it has become clear that solutions could perhaps be developed that provide pilot incapacitation redundancy. The continuation of this thesis will focus on SPCO and incapacitation; to determine what is necessary to ensure redundancy by other means than an on-board co-pilot. In Part 2, a SPCO flight scenario has been analysed with the aim of identifying the requirements for a Single Pilot Incapacitation Redundancy (SPIR) solution. Such a solution should provide redundancy of certain pilot functions; to the effect that the aircraft is landed safely.

Part 2

Single Pilot Commercial Operations: Pilot Incapacitation Redundancy

Chapter 10

The Incapacitation Redundancy Problem

The previous part of this report aimed towards understanding the main technical hurdles to SPCO, which resulted in a broad foundation of knowledge relating to the single pilot topic. The main challenges to realizing SPCO were found to be; providing the single pilot with the correct situational awareness at a manageable workload; ensuring redundancy in case of incapacitation; and, ensuring adequate monitoring of pilot performance without an on-board human co-pilot. To add depth to this work, one of the challenges to SPCO was chosen to be researched in greater depth. Currently, SA and WL receive significant research attention. In combination with current developments towards modernised ATM, the SA and WL challenges might be solved in the medium term future.

Incapacitation may be the most obvious and explicit reason for two pilots. According to C. Jackson, A320 type-rated commercial airline pilot, redundancy remains the most important reason for two pilots on conventional aircraft. “Just as there are separate autopilot systems and cross-linked hydraulic and electrical systems; redundancy is the primary reason for two pilot crews on commercial flights. Other reasons, such as increased alertness and increased awareness, are secondary” (Jackson, 2013). Chapter 7 has covered the different types of incapacitation. It was found that pilot incapacitation can be caused by medical events and external events relating to the physiology of flight. Of medical incapacitations, which can be considered to be a constant risk not dependent on aircraft design and externally caused events, roughly half were of cardiovascular nature and half were of psychological nature. Incapacitations of non-medical causation, such as acute hypoxia or less frequent bird-strike, are excluded from the scope of this research.

Part 2 aims to investigate potential solutions to the identified technical challenge of ensuring Single Pilot Incapacitation Redundancy (SPIR). The aim is to gain insights into the requirements for potential future SPCO, that would be a result of the need for incapacitation redundancy. Part 2 aims to answer the following two sub-questions first presented in the introduction (Chapter 1):

6. *What functions must an incapacitation redundancy solution for SPCO provide?*
7. *What are the most challenging functions to provide, and how might the SPFD be designed to overcome these obstacles?*

To uncover the implications of incapacitation redundancy on SPCO, it is aimed to identify the functions such a redundancy system must fulfil. The approach taken is as follows. The first step has been to come to understand the problem that pilot incapacitation presents. This has been done by means of a top-down functional analysis, as well as a bottom-up scenario analysis. The top-down functional analysis involves looking at the main function to be performed, and splitting this into individual subfunctions that would in combination achieve the highest level function. In applying the bottom-up scenario analysis, the chronological unfolding of events was assessed for a single pilot commercial flight scenario from Amsterdam Paris, in which an incapacitation would occur somewhere midway on the route.

The results of these two approaches provided an understanding of the functions required for an incapacitation redundancy solution in SPCO. The findings of the top-down and bottom-up analyses are presented in Chapter 11. Several conceptual solutions for each function were then composed. Through the development of these conceptual solutions, the most technically challenging functions required of an incapacitation redundancy solution have been isolated. Based on these functions, a hypothetical future FD concept is presented and discussed, in which these challenges would not be an issue.

The structure of Part 2 is as follows. Section 10-1 provides an estimation of the costs associated with incapacitation redundancy. Current SOPs for incapacitation events are explained in Section 10-2. Based on the rate of medical incapacitations, the research scope has been constrained; the topic of Section 10-3. In Section 10-4 assumptions are made regarding the SPFD on which the said functional analysis and scenario analysis are based. The range of potential incapacitation scenarios that could occur are categorized in Section 10-6. A short conclusion to this chapter is provided in Section 10-7. The findings of this chapter provide the foundation for Chapter 11, in which the required functions of an incapacitation redundancy solution are described; potential concepts explored; the most critical functions identified; and the findings related back to requirements for a SPFD of the future.

10-1 The Cost of Incapacitation and Motivation for finding solutions to SPIR

The aim of the detailed study of single pilot incapacitation is to better understand what requirements this issue induces to SPCO. As Part 1A of this thesis has illustrated, the evolution of crew size reduction has been halted at two for over three decades. Part 1B has found that this halt in crew size evolution is partly due to the challenge of incapacitation redundancy. If, crews have unnecessarily been oversized in the past, this will have incurred a great cost for society. This cost takes its form in terms of labor costs, but possibly also in the slowing of innovation towards safer flight decks. Considering the above, this is a reason to research if, and how, redundancy of a single on-board human pilot might be provided with other means than a second on-board pilot.

To emphasize the value of incapacitation research, one can crudely quantify the costs associated with incapacitation. Part 1 of this report found the frequency of occurrence of a medical incapacitation to be on the order of 5e-7 per flight hour, or equivalently, one incident in every 2 million flights. In 2011, 50.9 million flight hours were made world-wide with jet aircraft of maximum gross weight greater than 60,000 lbs (ASBCA, 2012). In the hypothetical situation that these aircraft had all been operated by a single-pilot with no means for redundancy in case of incapacitation, this would have resulted in roughly 25 fatal accidents in 2011 alone[1]. Furthermore, in 2011, there were 23.6 million departures of such jets. The addition to the world-wide fatal accident rate would be approximately one per million departures. That is a significant figure considering the actual ten-year fatal accident rate from 2002 through 2011 was 0.39 per million departures (ASBCA, 2012). Clearly, an addition of one fatal accident per million departures is an immense increase. Therefore, incapacitation redundancy is a very significant design requirement if SPCO are ever to be seriously considered. This is the motivation for studying the SPIR challenge in detail. The following section looks more closely at current SOPs for the event of incapacitation on multi-crew commercial aircraft.

10-2 Current Incapacitation Standard Operating Procedures

This section explains the procedures that take place in the event of an incapacitation occurring today. In current commercial jet aircraft, in case of an incapacitation, the actions of the remaining pilot depend mostly on which phase of flight the incapacitation occurs, and the task distribution (Pilot Flying vs Pilot Not Flying) is at that instant.

If the pilot identifies the incapacitation of the other pilot during take-off, yet prior to V1 (decision speed), the remaining pilot will immediately abort the take-off. If the incapacitation is identified after the decision speed V1 is reached, the pilot will continue to take-off and climb, immediately make use of the autopilot and radio stating a mayday and requesting a hold and a long approach (allowing more time for decision making and acting and thus lowering risk) for an arrival back to runway. The remaining fit pilot will use the Public Announcement (PA) system to request cabin crew assistance stating “CIC [Cabincrew in Charge] to the cockpit please” (Jackson, 2013). Cabin crew will proceed to enter the cockpit, strapping up the arms of the incapacitated pilot to prevent interference with controls, and remain in the cockpit to provide further assistance if needed.

Pilot training, SOPs and the flight deck design are integrated to be adept to this situation. Pilots are trained to make mandatory verbal call-outs during take-off if they are the Pilot Not Flying, and to re-call these speeds if Pilot Flying. Examples of call-outs during take-off are “thrust”, “one hundred knots”, and “V one”. After having called a call-out twice without a response, that pilot will immediately assume the other pilot is incapacitated and act accordingly. Call-outs are a Standard Operating Procedure that always occur during take-off and landing. The method in which pilots screen for incapacitation during high WL-high risk flight phases in current FDs, is a result of the limited time and attentional resources the pilots have available. An incapacitation during take-off or landing is an urgent situation.

If an incapacitation would occur at high altitude, such as 30,000 ft, the signals used to identify the incapacitation would be more subtle, such as unusual reactions to communications .

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[1] Based on the assumption that each of the 25 incapacitation events would have resulted in a fatal accident

If an incapacitation occurs mid-way along a route, the nearest acceptable airport would be identified by the remaining pilot in collaboration with ATC. Landing would proceed to provide medical assistance to the pilot, and to avoid flying with only one pilot. Considering conventional multi-crew flight decks, incapacitation presents the greatest risk when it occurs subtly, at low altitude, during a precision approach and in poor visibility conditions (ref skybrary).

This subsection has described what happens in case one pilot of a multi-pilot crew becomes incapacitated on-board a conventional multi-crew aircraft. An interesting point to note is that current multi-crew aircraft are designed for two pilots by requirement, but must also be operable by one pilot in either seat, specifically for incapacitation situations. Incapacitation is thus an inherent design consideration.

10-3 Incapacitation Rates and Research Scope SPIR

In Part 1B, the rate of incapacitation has been quantified. This allows the scope for the SPIR requirements to be constrained. Pilot incapacitation is a sufficiently rare failure condition that in the case of such a failure, the remaining aircraft and systems would not be required to cope with *adverse operating conditions*[2] For this reason, additional failures are excluded from the scope for the SPIR functional requirements and concepts. The most common factors that impact the outcome of an emergency situation are included in Appendix E for reference.

10-4 Assumptions regarding the Scenario Analysis FD

This section states the assumptions made regarding the SPFD on which the conceptual solutions and scenario analysis are based. This FD shall be referred to as the scenario-SPFD. Ideally, the scenario-SPFD would be synonymous with the actual future SPFD, if that is ever to exist. A challenge in performing this research has been that the disposition of a future SPFD is unknown. Part 1 did find that a future SPFD would be substantially different to current FDs. Due to this uncertainty, it was decided to base the scenario and functional analyses on a modern FD of today, but operated by one pilot. The latest Airbus A320 has been chosen as the scenario-aircraft. The A320 is a typical medium-range aircraft operated on the route considered for the incapacitation scenario and concepts; Schiphol, Amsterdam to Charles de Gaulle, Paris. In short, the assumptions pertaining to the scenario-SPFD and the scenario-aircraft are:

1. Based on a modern commercial multi-crew FD (Section 10-4-1)
2. Barriers to SPCO are overcome, except for incapacitation redundancy (Section 10-4-2)
3. Incorporates only technology in existence or development today (Section 10-4-3)

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[2] *Adverse operating conditions* are defined as "a set of environmental or operational circumstances applicable to the airplane, combined with a failure or other emergency situation that results in a significant increase in normal flight crew workload" (14 CFR 23.1309-1 E) (FAA, 2012d).

10-4-1 Based on a Modern Commercial Multi-crew FD

The scenario-SPFD is assumed to be similar to modern commercial multi-crew FDs. The single pilot is assumed to perform functions mostly similar to today's pilot functions. Because the redundancy concepts must somehow replace the essential functions of the pilot, it is important to define what these functions are. In recent years, the functions of the flight crew within the FD have been described in various similar ways:

- The most common definition is; a. aviate; b. navigate; c. communicate; and, d. manage systems.
- Billings describes the flight crew functions in slight different, yet similar wording; "to aviate (control the airplane's path), navigate (direct the airplane from its origin to its destination), and communicate (provide data and requests and receive instructions and information), and, increasingly in modern aircraft, to manage the resources available" (Billings, 1997, p. 16).
- A common more simplistic way of describing the functions to pilots in training is; a. fly the plane; b. where to; and, c. communicate what you're doing (Jackson, 2013).
- Another complete theoretical description of the flight crew functions is; a. flight management (aviating/primary control, navigating); b. communications management (ATC, crew members, other); c. systems management (monitoring and management of systems to perform particular functions); and, d. task management (Abbott & Rogers, 1993, p. 67).

These descriptions of pilot functions have in common that the immediate flying of the plane always has priority (maintaining lift, staying within the safe flight envelope), followed by the more medium-term directing of the aircraft (where it is headed). The additional functions of communications management, systems management, and task management aim to; a. support the essential functions (short and medium-term flying of the aircraft) and b. prevent complications that could obstruct the essential functions to be performed. The observation that the highest priority functions are aviation and navigation, and that the other functions exist to support the continuous provision of the primary functions, is important. Reference will be made to this observation in Section 11-1-2, in which it is discussed which former pilot functions must be replaced and how.

The captain's tasks conventionally include non-flying tasks such as taking care of passenger complications. The captain is the final authority on-board an aircraft. In extreme cases the captain is even required to leave his/her seat at the flight controls and apply attention to passengers. Because this is not a technical challenge, and could be solved by a reallocation of tasks and responsibilities to cabin crew, these tasks will not be considered further in this research.

A contemplated alternative approach to define the functions to be performed after the incapacitation, was to consider the aircraft an Unmanned Aerial Vehicle from the moment the single pilot becomes incapacitated. This would allow a system representation to be used based on the Abstraction Hierarchy (AH), resulting in a suitable interface accurately depicting the system constraints. Amelink formulated such a representation for an UAS (Amelink, 2010).

However, the incapacitated single pilot problem is constrained by the assumptions regarding the scenario-SPFD. Therefore, the functions to be performed by the SPIR concepts have been based on the pilot functions of current FDs rather than on the complete UAS system representation.

As Part 1 of this thesis report has argued, the design of the SPFD would involve a redistribution of tasks across the single pilot, on and off-board humans and technology, and automation. This restructuring would result in changes of less tangible aspects, such as cockpit cultural aspects. Cultural implications of a change to SPCO can be brought to light by viewing the entire lifecycle of the FD. For example, if flights are operated by one pilot, how would training take place? Certain valuable sources of learning will disappear if pilots fly solo. The interaction between two pilots during and after every flight are a valuable source of peer-review, resulting in self-reflection and learning. Due to crew rotation a pilot will typically flies with numerous varying pilots. The result is a circulation of information, skills, and learning among the entire pilot talent pool at an airline. By interacting with other pilots for the many hours of flight, a degree of cross-fertilization of ideas and knowledge of particular aircraft is thought to exist. These benefits would be lost, or should be replaced for the case of SPCO. Although such matters are not immediately obvious in this research, over an expanse of time and many FDs such matters would contribute to the overall safety of SPCO. For further reading on culture and the flight deck the reader is requested to revert to (Hutchins, Holder, & Perez, 2002), in which the history of culture-related ideas are reviewed, and a framework is sketched for the study of culture on the flight deck. In (Hutchins, Weibel, Emmenegger, Fouse, & Holder, 2013) an “integrative approach to understanding the flight crew activity” is described, based on the most recent innovations in cognitive science theory. The cultural impacts of SPCO are left for further detailed study, as this research focuses on incapacitation. And yet, the likelihood of incapacitation might well be impacted by the absence of a co-pilot (companion) from the FD.

10-4-2 Barriers to SPCO are overcome, except for Incapacitation Redundancy

The main technical hurdles to SPCO identified in Part 1 are assumed to be (in some unknown way) solved in the FD for the scenario analysis. By assuming that these challenges are solved, but avoiding specifics, these issues could be excluded from the design scope. The challenges to SPCO that are assumed to be solved are WL, SA, and PM. Future solutions to high WL, low SA, and PM will most likely impose significant alterations to the SPFD (as predicted by Part 1). Because it is highly uncertain what these alterations would be, no assumptions have been such alterations. It is quite possible that the alterations will aid to solve some incapacitation related issues, and also create new issues. Yet, because the uncertainties are too high, it will simply be assumed the scenario-SPFD is largely similar to the conventional multi-crew FDs. The only assumptions made about how the technical hurdles to SPCO are solved by new technology, are those stated in the following subsection or discussed elsewhere in this thesis.

An issue identified in Part 1 was that of checklists. Checklists present an issue in multi-crew FDs, where checklists exist as a safety feature, and yet are also a cause of accidents. The purpose of checklists is to increase SA, as well as induce a degree of performance monitoring (PM) within crew behavior. In SPCO the manner in which checklists can be applied will be different. Pilots would not be able to split tasks as in multi-crew FDs. Hence, during non-normal conditions it is unlikely the single pilot will have the time or attention to complete checklists in their current form. This matter would be complicated if more (complicated) checklists are needed as a result of increased aircraft complexities. This and other issues are assumed to be solved in some way for this research, to allow a focus on the incapacitation issue.

10-4-3 Incorporates only Technology in Existence or Development Today

Certain technologies that can be expected to be available with moderate certainty are assumed to be available on the FD or external infrastructure of the air transport system. Only technologies described in Chapter 8 and predicted to be available by the year 2020 are assumed available on the scenario-SPFD. The technologies assumed to be available on the FD that are not present on conventional FDs are:

- Based on the findings of Section 8-2 concerning ATM updates, it will be assumed that some form of 4D trajectory planning will be available in Europe by the year 2020. This is expected to facilitate ATC in identifying potential conflicts and assuring separation. 4D trajectory planning is also assumed to improve the context awareness of on-board automation.
- As described in Section 8-3, Adaptive Automation is in the initial development phase. AA is limited by the challenge presented by precise inference of OFS. OFS estimation is assumed to be implemented merely to provide a basic form of adaptive support, relating to non-critical functions only, but no adaptive automation. Currently, high operator stress levels can be crudely identified, yet inference of the OFS is highly dependent on calibration for individual operators. A major challenge that exists lies within ambiguities in inference of states.
- Though inference of OFS based on psychophysiological measurements currently remains in the initial development phases, the measurement of psychophysiological markers including most importantly heart rate, is currently well developed. This is illustrated by the rapid expansion of reliable and unobtrusive personal wearable health monitoring devices available. It is expected that by 2020 these technologies will be thus far developed that observation of psychophysiological markers including heart rate, gaze direction, and breathing rate will meet accuracy, reliability, and unobtrusiveness requirements, to realize autonomous monitoring for cardiovascular incapacitations. A major challenge does exist with respect to sensing of psychophysiological markers in the high-magnetism environment of the cockpit.

The following section explains the research process of Part 2 in detail.

10-5 Research Approach SPIR

As stated, the goal of Part 2 of this thesis has been to better understand the challenge incapacitation presents to achieving SPCO. This has been taken on by exploring the functional requirements that a SPIR solution must be fulfil.

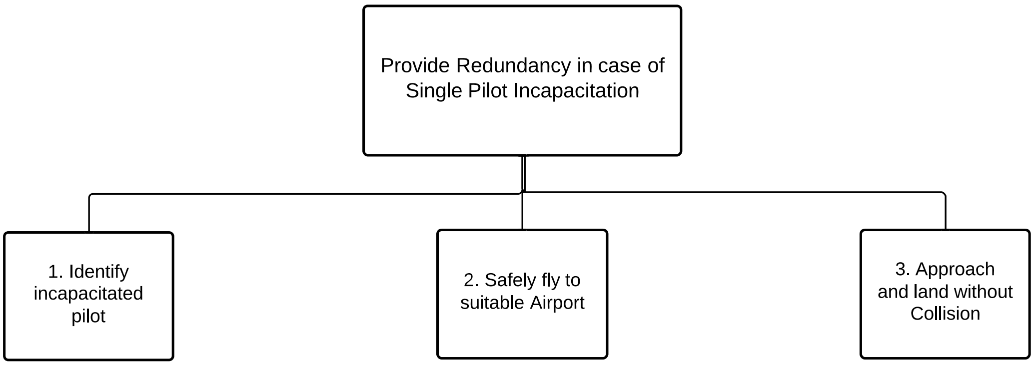

Figure 10-1: Top Level of Functional Breakdown illustrating initial conception of SPIR functions.

Following a phase of context-explorative research, an initial Functional Breakdown (FB) was created for an incapacitation redundancy solution for the scenario-SPFD described in the previous section. Figure 10-1 depicts exclusively the top level of this initial FB. The complete FB is available in Appendix F. This FB was used at the start of the research of Part 2, to crudely present the SPIR functions required; from high-level to low-level. Each (sub)function of the FB was then researched in more depth, to determine how challenging it would be to provide this function. Because the FB was an initial guide to the research, no detailed explanation or reference will be made in regard to the subfunctions. The three top level *functions* in Figure 10-1 are segregated more in terms of time-span, than the segregation of appropriate individual functions. As the research progressed, a better understanding of the ideal isolation of functions was developed, which is presented in Chapter 11.

In addition to the top-down research, a bottom-up technique was applied in the form of a scenario analysis. The scenario investigated was that of an incapacitation occurring to a SPCO en-route from AMS to CDG. In performing the scenario analysis, functional requirements (and practical matters and challenges) were uncovered from the bottom-up, by considering the unfolding of the incapacitation event, and which particular actions or tasks would need to be fulfilled now that the single pilot was incapacitated. Together, these analyses created a comprehensive understanding of the challenges to land the aircraft safely once the pilot was incapacitated.

The findings of the top-down functional analysis and bottom-up scenario analysis have been combined, taking the form of a Functional Decomposition. This Functional Decomposition best illustrates the essential top-level functions required of an incapacitation redundancy system, in a way that isolates the main challenges. A number of concepts for each function are described in short, to illustrate these main challenges to the reader. Finally, a hypothetical future flight deck concept for SPCO has been discussed, in which the main challenges would be mostly overcome. This flight deck is the topic of Section 11-2.

During the research, the approach had to be refined based on what was learned. The initial intention was to perform only a single detailed scenario analysis to uncover the requirements and challenges for a SP redundancy solution. However, as the research progressed, it became clear that the range of potentially occurring scenarios was too broad to capture the requirements by performing one scenario analysis in detail. To gain the greatest value from the research, it was decided to expand the research by exploring the main dimensions that characterise any incapacitation event. In this way, concepts have been devised that would be more adept to each of these scenarios. In other words, it has turned out that it is precisely the large diversity in possible scenarios that makes the conceptualisation of an incapacitation redundancy solution so challenging. For this reason, the functions were isolated in a way (displayed in the Functional Decomposition) such that the fulfilment of each function could be effectively considered for the entire range of possible scenarios.

The initial Functional Breakdown (Figure F-1) is included in Appendix F. The dimensions identified that characterise the set of possibly occurring incapacitation scenarios are presented in Section 10-6. The Functional Decomposition (Figure 11-1) and the possible concepts fulfilling the most important functions are the topic of Section 11-1-1. Finally, the hypothetical future flight deck concept is discussed in Section 11-2.

10-6 Dimensions Characterising Potential Incapacitation Scenarios

In determining which scenario would be most valuable for an analysis, it was found that the potential developments in a scenario (even when limiting the scope to the AMS-CDG route), could vary greatly depending on particular factors. One such factor is the phase of flight in which the incapacitation occurs. Another factor is the mode of the autopilot that is employed (if any) at the time of single pilot incapacitation. The main factors have been identified that would impact the specifics of the scenario; the unfolding of events; and the subsequent requirements for an incapacitation redundancy system. Additional failures occurring on top - or already present at the time of incapacitation - would highly impact the unfolding of events. But as stated before, additional failures are excluded from the scenarios for this research.

As explained, the scenario analysis and the top-down functional analysis have clarified what the major factors are that impact the outcome and redundancy requirements for SPCO incapacitation events. The dimensions is suggested to be used to characterise all incapacitation scenarios, including falsely identified incapacitations, are:

- Flight phase.
- Automation mode enabled.
- Interrupted pilot tasks, decisions, and commands.
- Type of medical incapacitation.
- Diagnostic test outcome for incapacitation detection.

10-6-1 Flight Phase

Phase of flight (take-off, initial climb, climb flaps retracted, en-route cruise, descent, initial approach, final approach, landing). Landing and approach are the most critical phases of flight, yet they are also the most complicated situations in which to take over control from an incapacitated pilot. On top of the urgency of the situation, the flight phase also impacts what the immediate actions must be after the incapacitation is verified. Most importantly, the required primary control actions vary significantly depending on flight phase. The flight phase in which the incapacitation occurs also determines if any supporting tasks are required, such the adjustment of altimeter settings depending on altitude; essential to maintain separation. Clearly, the requirements are highly dependent on the flight phase in which the incapacitation occurs.

10-6-2 Automation Mode Enabled

The manner in which a scenario will develop in case of an incapacitation depends highly on the automation used at the time. If no (or an unsuitable) automation mode is active at the time of incapacitation, this will increase the complexities in seamlessly taking over the controls from an incapacitated pilot. The automation modes available on current Airbus A320 aircraft are auto-thrust, vertical, lateral control modes. A more generic way to view this dimension, is in terms of the level of automation as described by the Sheridan-Verplank scale of human-machine function allocation in automated systems (Sheridan & Verplank, 1978).

10-6-3 Interrupted Pilot Tasks, Decisions, and Commands

The specific tasks, functions, decisions, or actions the pilot was making or performing at the time of incapacitation determine the immediate functions that must be continued by other means than the pilot. Any incapacitation redundancy solution must be able to take over primary control from the pilot in a safe and seamless manner. The solution, whether human or automated, should be aware of what the pilot is doing at each stage of the flight, and be able to continue off from where the pilot left off. As stated above, if a mode of automation happens to be in use that will direct the aircraft along a safe route immediately after the incapacitation takes place, this will severely impact safety for the better. If the pilot was in the midst of critical actions during manual control, the threat to safety would be much more severe and immediate.

10-6-4 Type of Medical Incapacitation

As stated before, only medical incapacitations are considered in this research. The type of incapacitation determines how effectively a reliable identification could be made by other means than a second pilot. The most common forms are cardiovascular, psychological and gastrointestinal illness. SP-incap should be able to identify at least incapacitations, and possibly impairments. As defined in Section 7-1, an incapacitation is likely to result in loss of control of the aircraft, where as an impairment is defined as being of lesser severity and/or duration, such that the pilot can land the aircraft safely. Incapacitations are thus most important to recognise, and provide redundancy for.

10-6-5 Diagnostic Test Outcomes for Incapacitation Detection

The set of diagnostic outcomes to a test for incapacitation illustrates that for the design of an SPIR solution, it must be explored what would happen if false diagnoses are made. In a conventional multi-crew flight deck, it could potentially occur that the Pilot Not Flying fails to hear the re-calls of the Pilot Flying, and takes over the controls unnecessarily. In this situation, there would still be a human at the controls, and the pilots could proceed to resolve the issue when times permits. In the SPCO situation, an unjustified take-over of controls may have much worse consequences. Especially if the fall-back means of control is less skilled than the pilot, and/or if the take-over occurs in a discontinuous manner. This illustrates that not only is it beneficial that actual incapacitations be identified correctly within an acceptable timeframe, but that a false identification of incapacitation should not unnecessarily threaten flight safety. This raises the issue of setting the correct incapacitation identification sensitivity threshold; the estimated pilot health level at which the pilot is judged to be incapacitated. The challenge of setting the correct thresholds is discussed in Section 11-1-1. Clearly, the performance of diagnosis of incapacitations is a safety critical matter. Monitoring for incapacitation should occur continuously. An incapacitation pilot event can be true or false at any moment, and the diagnosis can be correct or incorrect, forming the following scenarios:

- True positive (correctly identified incapacitation)
- False positive (a diagnosed incapacitation that is incorrect; the pilot is actually fit to fly)
- True negative (correctly identify a healthy pilot state)
- False negative (failure to identify an actual incapacitation)
- Delayed true positive (An actual incapacitation identified correctly, but only after excessive time)

During the scenario analysis it was found that a diverse range of scenarios can occur. This section has presented five key dimensions that define the characteristics of any incapacitation scenario. These factors were found to be; the flight phase; the suitability of any automation in use; any interrupted pilot tasks, decisions, and/or commands; the type of medical incapacitation; and the outcome of a diagnostic test for incapacitation. These findings have led to the understanding that an incapacitation redundancy solution must be highly versatile.

10-7 Conclusions Incapacitation Redundancy Problem

This chapter has outlined the problem incapacitation presents to single pilot flight decks. If all current large jet aircraft were to be operated by one pilot without a means for redundancy, this would result in an addition of 1 fatal accident per million flight hours, to the current rate of 0.39 fatal accidents per million flight hours. The incapacitation-related SOPs of multi-crew operations have been explained. These SOPs are found to be aimed at identifying an incapacitation with immediacy during take-off and landing, allowing the remaining human operator to seamlessly take-over or continue controlling the aircraft. During less critical flight phases, no SOPs exist, but the interactions between the pilots is relied on to uncover an incapacitation. Hence, the immediate and seamless continuation of flight especially during the critical flight stages, is the most pressing matter in case of incapacitation in multi-crew FDs today. Because current aircraft are by requirement operable by a single pilot (at least in normal operating conditions), landing the aircraft safely is within the abilities of the remaining pilot. In addition, the pilot can count on support from cabin crew and VIP (Very Important Plane) treatment from ATC.

The functions required of a SPIR concept have been investigated for a SPFD in which the pilot performs similar functions as in current FDs. The identified functional requirements have been identified by means of a top-down functional analysis, and a bottom-up scenario analysis. A major finding was that the range of incapacitation-related scenarios would vary greatly, according to; the flight phase; the automation mode enabled; any interrupted pilot tasks, decisions, and commands; the type of medical incapacitation; and the outcome of a diagnostic test for incapacitation. A result of the analyses is a Functional Decomposition outlining the required functions for SPIR. This Functional Decomposition provides the foundation for the following chapter, in which potential solutions to SPIR are explored.

Chapter 11

Functional Requirements for SPIR Concepts

This chapter presents the single pilot incapacitation redundancy concepts. Section 11-1 illustrates the higher level functions identified as a result of the previous chapter. The Functional Decomposition shows clearly *what* functions a SPCO redundancy concept must provide. Several possible solutions as to *how* the required functionality can be provided are presented in Section 11-1-1. Based on these conceptual solutions, some key technical challenges are highlighted; the topic of Section 11-1-4. Finally, a hypothetical future SPFD concept is discussed that has the potential to overcome these challenges. This concept re-ignites a number of existing debates regarding the role of humans and automation within aviation.

11-1 Concept Exploration

The exploration of the incapacitation problem, presented in the previous chapter, has led to a better understanding of the design requirements. As a result, a depiction of the functional requirements has been made, that best isolates the key functions. Solutions for each essential function could then considered separately.

The main goal that the Functional Decomposition aims to solve is described by the mission statement;

> *The single pilot incapacitation redundancy solution must ensure the aircraft is landed safely and brought to a standstill on the runway, in the event that the sole pilot on board becomes medically incapacitated, during any phase of flight.*

For this initial research, the limitations on the scope are such that; no additional failures or adverse operating conditions occur; coverage must be provided only for the heavily operated routes within Western Europe; redundancy must be provided for all flight phases.

Furthermore, a number of assumptions were made regarding the FD (Section 10-4); the FD is assumed to be mostly similar to a modern commercial multi-crew FD; the single pilot is assumed to perform functions similar to today's pilot functions; the main technical hurdles other than incapacitation redundancy are assumed to be solved in some way; the FD only incorporates technologies that exist or are in development today.

11-1-1 Functional Decomposition

The analysis of the preceding chapter has led to the isolation required functions for a SPIR concept. As the research progressed, the representation of the main functions developed from the initial Functional Breakdown. The revisited representation of the high level functions is a more generic description. This functional decomposition is presented in Figure 11-1. Each main function can now be more suitably isolated as a separate design problem. This section presents some feasible concepts for each high-level function.

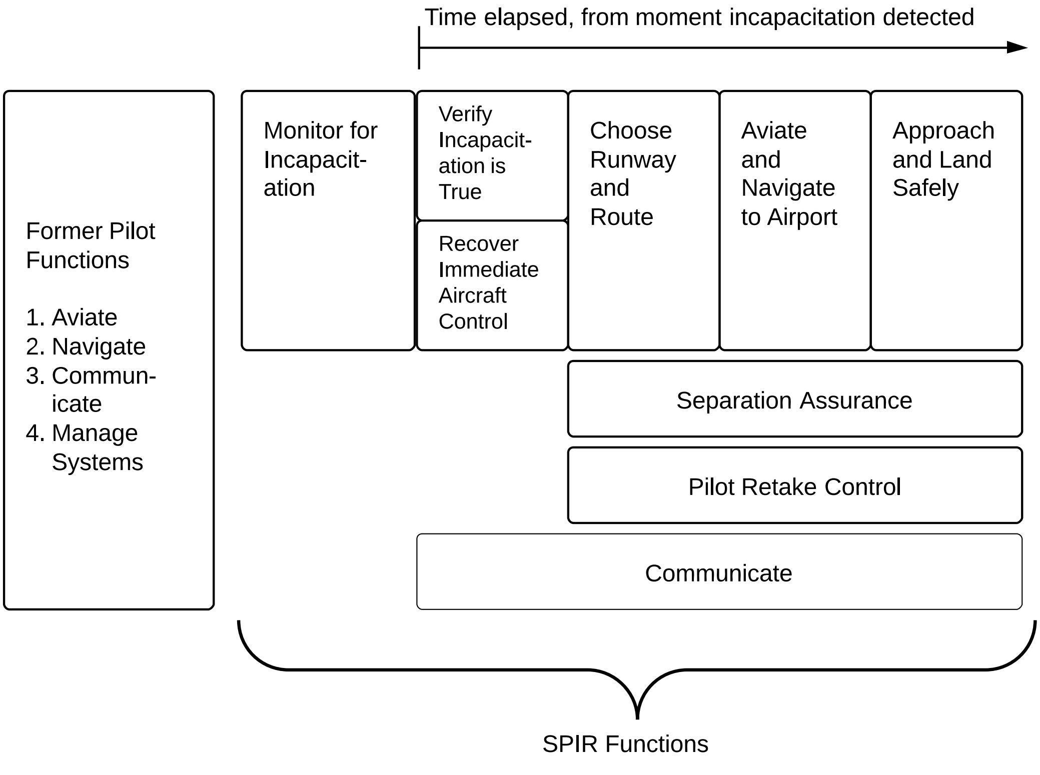

Figure 11-1: Generic Functional Decomposition illustrating the essential incapacitation redundancy functions.

11-1-2 Concepts for each Function

The previous subsection presented the main functions to be provided by an incapacitation redundancy solution. The main functions depicted in Figure 11-1 are described below. Each function of the Functional Decomposition is explained and any requirements are stated. For each function, some concepts are shortly discussed. In some cases, it becomes clear that certain concepts would not meet the requirements alone but may do so in combination.

Former Pilot Functions

Former Pilot Functions refers to the functions normally provided by the pilot, should no incapacitation occur. As explained in Section 10-4, the formulation of the pilot functions adhered here are the same as that for modern multi-crew aircraft. The highest priority pilot functions are to aviate and navigate. The other functions do not in themselves fulfil any higher level goals, yet are required to support the continuous availability of the primary functions. The above observation allows the focus to be laid on the aviate and navigate functions, as long as the following two subresearch questions are answered.

> *To achieve a safe landing without threatening the safety of other aircraft, what communications must occur?*
>
> *Considering the assumption that no additional failures occur, what systems must be managed to achieve a safe landing?*

For this research, it will be assumed that communications are only necessary to achieve the higher level functions. Furthermore, the systems management function will be excluded from the scope at this stage. The reasoning is that the systems on board complex aircraft increasingly manage themselves. The role of pilots is becoming more one of systems supervisor than a systems manager. Hence, the former pilot functions of systems management and communication have not been included in the final Functional Decomposition.

Some concepts led to the observation that the routine *Former Pilot Functions* should be adjusted if that facilitates the SPIR functions to be performed in case an incapacitation should occur. An example of a potential change to pilot functions is the pilot's active involvement in alerting the redundancy system if he/she feels unfit to fly. Another potential change to the routine pilot functions is the preventative entering of alternative runways and routes in the FMS as part of pre-flight procedures. An optimal SPIR concept would achieve the main functions as much as possible within the confines of the aircraft, retaining a mostly self-sufficient FD.

Monitor for Incapacitation

Incapacitation redundancy in multi-crew operations allows immediate and seamless continuation of flight in critical flight stages. During non-critical flight stages, monitoring is performed in a less formalized manner, based on the interactions between pilots [1]. Thus monitoring for incapacitation occurs continuously during critical flight stages, and quite regularly during the other flight stages as a result of there being two pilots. In the single pilot situation, monitoring for incapacitation must therefore occur continuously during all flight phases. A potential incapacitation must be identified nearly immediately because take-over will very likely be less seamless as can be achieved by a second pilot already at the controls.

Because an incapacitation must be identified with immediacy, alert threshold design becomes a critical issue, as explained in Section 10-6. Too many false warnings could result in novel dangerous situations due to a distracted pilot, and could even condition the pilot to reject incapacitation warnings without due consideration, reducing the effectiveness in an actual incapacitation situation. The threshold parameter is the severity of the estimated pilot's state, which would in turn depend on the means used to estimate the pilot's state, for instance (remote) human eyes, or an autonomous sensory-based monitoring system. The most suitable threshold level depends on urgency to recover the aircraft, which depends on the flight phase. Threshold design also depends on the severity of results of negative warnings, which is again proportional to flight phase criticality. Hence, threshold setting is a major design challenge, potentially even a determinant of the feasibility of the system.

Because there is no second pilot on board, *Monitor for Incapacitation* must be performed by some other means. A number of concepts could be combined to create a means that would have better performance at identifying incapacitations with sufficiently few warnings, during all, but especially the critical phases of flight. Incapacitation identification could be provided by:

1. Autonomously, based on performance markers and psychophysiological markers, and inference of OFS.

2. By the pilot alerting the aircraft based on self-surveillance.

3. By means similar to a 'command loss timer', as used in spacecraft such as Voyager 2, whereby the operating state of the craft is reset if no control commands are received for a certain period. This system aims to recover the spacecraft from malfunction that might lock it into a mode in which it cannot receive new commands (Moore, 2007).

4. By means of an alerting system similar to that on locomotives, where the engineer must respond to a periodic consultation by pressing a button. Failure to do so activates the emergency brakes. In aviation, such a system is feasible for long haul flights. The urgency in case of critical flight phases is too high for such a solution.

5. By means of a cabin crew member joining the pilot during critical flight phases. Then, if the pilot becomes incapacitated, the crew member initiates the *Recover Immediate Aircraft Control* function (explained below). This could essentially provide the *Monitor for Incapacitation*, as well as the *Verify Incapacitation is True* functions at once. This concept would not be a suitable sole means for an entire flight.

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[1] Monitoring for sleeping pilots is performed using systems such as EPAM and excluded from the research scope

Verify Incapacitation is True

Verification of an incapacitation identified in the foregoing function must be completed rapidly, yet should allow the pilot ample time to reject the identified incapacitation. For this function, the setting of the time limit threshold for rejecting a false incapacitation identification is a key design driver. Concepts are:

1. Requesting the pilot to perform some action if the identified incapacitation is false.
2. Cabin crew joining the pilot in the cockpit during safety critical flight phases, as explained above.
3. Via audio or video communications with cabin crew or with humans external to the aircraft, to keep humans in the loop before the control is taken away from the pilot.

Recover Immediate Aircraft Control

The purpose of this function is to seamlessly continue from where the pilot left off, returning the aircraft to a safe flight condition (and flight path). This function is performed only in the event of the previous function *Verify Incapacitation is True* resulting in a verification. The urgency of the *Recover Immediate Aircraft Control* function increases with flight phase criticality (due to the time-risk relationship; the low altitude and low velocity nearer to stall conditions; and the close proximity to the ground during landing). Ideally the conceptual solution for this function would have an awareness of the planned and actual flight path and aircraft conditions. These could be compared, to determine what actions are required to *Recover Immediate Aircraft Control.* Thus, this top level function introduced some challenging subfunction requirements.

Seamless take-over of control might be a task more suited for humans. Adaptability is a skill for which humans are known, and automation not so much. Depending on the severity of the aircraft state, seamless recovery may well require the adaptability of a well trained human pilot. However, the advances in automation may shift the perception as to skills of humans and those of automation. Either way, the extent to which an aircraft's conditions may deteriorate depend on the immediacy with which the previous two functions are completed. The immediacy with which the previous two functions are completed was shown to depend heavily on the ability to set suitable sensitivity thresholds. Again, the impact of threshold design is clear. Possible concepts are:

1. The pilot always performs critical flight phases on full autopilot, so that if incapacitation occurs, seamless continuation of the planned flight would occur initially, assuming no failures or adverse operating conditions occur.
2. Both the performance and range of skills of automation may have expanded by the year 2020 to perform the subfunctions to achieve autonomous recovery even from extreme flight conditions. Autonomous recovery from extreme flight conditions is a technology applied before in fighter jets, in case pilots become unconscious due to high g-loading. Autonomous recovery of aircraft control appears realistic. The deviation of actual flight

path from planned flight path could be used as a measure of pilot health, for the *Monitor for Incapacitation* function. Because a pilot might purposefully deviate to avoid unanticipated hazards, this raises basic issues relating to humans, automation, authority and trust.

3. By remote take-over of control by a team of co-pilot(s) located somewhere on the ground, who are always prepared for such a situation occurring. As roughly estimated in Section 10-1 based on medical incapacitation rates as found by Evans (Evans & Radcliffe, 2012) and DeJohn (DeJohn et al., 2006), and on global flight hours of jets over 60,000 lb maximum gross weight in 2011 (ASBCA, 2012); roughly 25 such incapacitations would occur annually world-wide. This figure gives an indication of how busy such a team would be, supposing the coverage, continuity, and bandwidth issues of the required digital communication links are overcome. Such a team of experts could provide support for other non-normal conditions.

Choose Runway and Route

In case of an incapacitation, the aircraft may have to divert from the original flight plan. The reasons for this are to prevent an extended duration of a high-risk flight condition but also to allow the pilot to receive medical treatment. It is common practice to return to the departure airport, deviate to an alternative suitable en-route airport, or continue to the destination airport depending on the postion along the planned route. This is a decision the remaining pilot would make in conventional multi-crew operations. The optimal route depends mostly on the location of the optimal runway, and presence of hazards such as adverse weather conditions and obstructive terrain along the route. Factors such as wind velocity are already incorporated into current FMS. Runway length, runway maintenance state, visibility and weather conditions, the availability of medical assistance impact the choice of runway by the remaining pilot in incapacitation scenarios today. If the pilot would have a choice, VMC would be preferred; permitting the pilot increased heads-up time. The optimality of a runway and route in the case of SPIR depend on how - and how effectively - the *Approach and Land Safely* and the *Aviate and Navigate to Airport* functions are performed.

The likelihood that runway information is up-to-date must play a role in choosing a runway. In Europe, ample well-maintained runways exist that are suitable for an A320 to land. This allows a clear split between this, and the next function; *Aviate and Navigate to Airport.* Possible measures to choose the runway and route are:

1. By means of autonomous on-board optimization of a cost function to minimize risk, based on decision parameters and a database of runways and their relevant characteristics.

2. By allowing control of the aircraft from a manned remote ground station in case of an incapacitation. Through higher level control commands to limit communications bandwidth, and increase likelihood of sufficient continuity of communications link to send commands. In this way a human can be kept in the loop in choosing the runway and route.

3. For completeness, it is considered that this function might be performed by trained cabin crew. However, based on the common conception that a good pilot is a pilot that is always learning, and pilots train for many years and learn throughout their entire careers, it seems unlikely that cabin crew can provide such critical functions as choosing the correct runway. Furthermore, choosing a suitable runway could very easily be allocated to specialized humans on the ground, requiring only simple communications means. It is only wise to keep the human in the loop if that human is adequately trained to perform the required functions.

4. As explained in regard to the *Former Pilot Functions*, a possible concept is that the pilot pre-sets alternative runways in the FMS as part of routine pre-flight procedures. This solution keeps a human in the loop, albeit pre-emptively, and ensures the aircraft is self-sufficient for this function.

5. Based on current developments in autonomous context awareness, it is highly likely automation of the flight deck in 2020 will be capable of autonomously avoiding hazardous weather and terrain.

Aviate and Navigate to Airport

This function excludes the immediate recovery of aircraft control, which is assumed to be performed once this function is needed. In this conceptual design, the aviate function (to "control the airplanes path" (Billings, 1997, p. 16)) and the navigate function (to "direct the airplane from its origin to its destination" (Billings, 1997, p. 16)), are considered as a combined function. Because in current FDs the aviate function is performed by autopilot a significant proportion of all flight phases, it will be assumed the aviate function will be provided by the autopilot in a SPIR concept. In the event that no other failures or adverse operating conditions occur, the autopilot would provide the aviate function without failure. That limits the concepts here to the navigation functionality. The previous function results in a chosen runway and route. The information regarding the choice of runway and route will need to be communicated to the element responsible for directing the aircraft to the destination. If these functions are performed on-board the aircraft, that would simplify the reliance on communications. An important requirement is that the aircraft must not be in excess of the Maximum Landing Weight upon arrival at the runway. [2] The Maximum Landing Weight must be considered in the choice of optimal runway and route, as a requirement of safety.

1. If the choice of runway is made by a cost function run on the FMS, and the FMS is also responsible for directing the aircraft to the destination and along the chosen route, the function is simply provided.

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[2] Based on a fuel flow rate of 2,600 kg/hour and 2.5 hours of flight (including one extra hours worth of contingency fuel), the AMS-CDG route requires approximately 6,500kg of fuel. The Maximum Landing Weight of the A320-200 is 64,500kg. The sum of the Operating Empty Weight (42,000kg), the Maximum Payload (18,600kg) and the calculated fuel load (6,500kg) amounts to 67,100kg; 2,600kg in excess of the Maximum Landing Weight (AirlinesInform, 2010). By this crude calculation, if an incapacitation occurs just after take-off, 2,600kg of fuel must be dumped in the air or the aircraft must remain airborne for one hour, in order to land safely. These costs should be taken into consideration in outweighing the costs and benefits of SPCO. For the route considered, the destination could nearly be reached within one hour of flight. Whether this would be desirable depends on the likelihood of additional failures, which is outside the scope of this research.

2. If the choice of runway and route is made from a manned remote ground station, the commands to direct the aircraft must be communicated to the aircraft. In this case, the commands would likely be higher level commands, implying that an on-board human or interface would still be required to implement them. Again, the simplest and tried and proven solution for the implementation appears to be via the FMS. For reason of security, it may be wished to keep a human in the loop within the aircraft, in case of a security breach. Such a concept would be rather complicated.

Approach and Land Safely

Approaching and landing safely might be performed in different ways. It must be considered visibility in Europe is often poor, requiring the use of ILS. However the *Aviate and Navigate to Airport* function is provided, in poor visibility, the approach and landing will always require guidance by other means than visual. This is the case whether aviation and navigation occurs by means of remote control or autonomously using existing FMS and autopilot modes, or in some other way. The *Approach and Land Safely* function refers especially to how the guidance during the approach and landing is provided.

If a runway is available that does offer VMC, ILS will not be essential only if there is a means to aviate and navigate the approach and landing based on visual reference. This would be possible if there happens to be a second pilot on board, or if remote control is performed based on visual references, such as streaming of a video feed from the cockpit. Because a second pilot is assumed not to be among passengers most of the time, and cabin crew would require so much training this would be more synonymous to multi-crew operations, that option is excluded. As has been stated before, the remote control option is excluded from the scope of this research.

The reason is that a remote control option would put the hardware and software in place for potential remote hijacking. Although this might be judged as nearly impossible if advanced security systems are incorporated, it is also extremely difficult to accurately estimate how rare such an event might be [3]. Even if frequency of occurrence of remote hijacking would be extremely rare, this could be off-set by the unfathomable severity of such an event. It would be beyond catastrophic if all airborne aircraft would be simultaneously remotely-hijacked. The potential damages could extend far beyond that of the aircraft and passengers, if damage on the ground is included. This scenario may appear as an unrealistic Hollywood movie scenario. And yet, the events of the Fukushima Daiichi nuclear disaster illustrate that any conceivable situation must be seriously considered. Remote control is mentioned as a potential means to approach and land safely for completeness sake. The above presented issue is a significant argument against this option; the risks of remote control might very well outweigh the benefits to SPIR. Below, several other options are presented that could provide the means to *Approach and Land Safely*:

1. The most obvious solution to landing the aircraft in case the pilot is incapacitated is by means of the automation already on-board. Current A320 aircraft are fully capable of

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[3] The rarer an event is, the more uncertainty exists in the estimation of its likeliness. Humans are notoriously poor at estimating the likeliness of very rare events. As the unlikeliness of an event increases, fewer examples of such event will have occurred on which to base the estimation calculations for frequency of occurrence. Furthermore, if new scenarios are created, such events will never have occurred before.

landing the aircraft in normal operating conditions in conjunction with an ILS system of at least CATII rating (Jackson, 2013). The required systems (landing gear, flaps, throttle and thrust reversers, ground spoilers, and autobrake/including wheelbrakes) are sufficiently integrated to bring the aircraft to a safe standstill on the runway; according to A320 pilot C.Jackson, “the aircraft is absolutely outfitted to do it; it follows the LOC and puts the aircraft to a halt.” (Jackson, 2013). ICAO regulates the use of ILS. Currently, all but CATIII ILS require visual verification of the runway at the DH, which the PF and PNF would normally perform. To land the A320 making full use of the on-board autopilot, the pilot would normally perform the following operations, which must be performed in some other way to achieve SPIR:

   (a) Program the type of arrival; STAR, RNAV, ILS, NDB, VOR arrival.
   (b) Put in the weather conditions; barometric pressure at airfield, temperature, wind direction, and min decent altitude.
   (c) Program the missed approach procedure in the FMGC.
   (d) Elect the type of braking systems; Low, medium or max. The autobrakes and speed brakes activate automatically, as long as the pilot has armed them.

2. Another option would be to use the on-board FMGS and autopilot to land using CATI, II, or III ILS in combination with a. remote verification from manned ground station via video feed of flight deck view that runway is in sight, or b. verification that the aircraft is suitably lined up for landing by an observation system on the ground at the start of the runway. If improperly lined up for landing, the aircraft should be ordered to perform a go-around. ILS do not provide guidance for go-around.

3. MLS has been implemented as an option on modern Airbus A320s since 2007, but is currently provided at limited airports only. Runways equipped with MLS provide increased coverage area reducing the likeliness of a missed ILS capture. MLS also provide guidance for a take-off (go-around) in case of missed approach. However, it is generally expected that augmentation of GPS will overtake MLS in the future. Hence, MLS implementation is expected not to become ubiquitous. It would be more practical to make use of the existing runway ILS or GPS-based systems and accept the current limitations. The impact of these limitations are rare, and may well be solved by 2020. Because incapacitations are rare, and ILS failures are rare (ILS installations are periodically tested by specialists representing aviation organisations), it is very possible that the requirement for visual verification of the runway at the DH may be neglected. According to Jackson, complications that might occur are; “the ILS or LOC might fail; excessive wind gusts; or the aircraft may not be able to handle the automation and the weather at the same time. This is not likely at Amsterdam Schiphol, Paris CDG, or London Heathrow, but at smaller airfields it can happen every now and then” (Jackson, 2013).

Separation Assurance

The means to provide separation assurance will depend on how the *Aviate and Navigate to Airport* and the *Approach and Land Safely* functions are provided. Although separation assurance is a important function for maintaining safety, it poses only a limited challenge to realizing a SPIR solution. This hypothesis is based on the fact that in current mayday situations, the assurance of separation from other aircraft is commonly performed by ATC, who instruct aircraft in the vicinity to deviate; giving priority to the mayday call. ATC must then be aware of the intentions of the aircraft suffering incapacitation, requiring communication between the elements providing the various functions. For instance, ATC would need to be informed when an incapacitation occurs and on which aircraft, as well as the planned runway, route, and timing of landing.

To allow ATC to provide separation assurance, the correct altimeter value must be set on the flight instruments of the FD. Whether or not this is already automated or not, it is assumed that by 2020 the altimeter setting will autonomously be adjustable to QFE for specific aerodrome height. If the incapacitation occurs above the transition level, two-way communications must occur between the aircraft and ATC to request and read back the altimeter setting. Apart from the reading back of the altimeter function when there is no fit pilot on-board, this should pose no new issues.

Pilot Retake Control

One might consider that if an autonomous SPIR solution fails, and the pilot recovers from bad health, the pilot would wish to retake the controls. The pilot should only retake control if truly fit to fly the aircraft. This is not a major design consideration at this early stage.

Communicate

As stated above, the required communications are a resultant of how the various functions are provided. The communicate function is therefore described within the subheadings of those functions.

11-1-3 The Optimal Concept

During the scenario analysis and considerations of the various functions, a concept has evolved that appears to be most realistic. This concept is nearly entirely self-sufficient; redundancy is provided with minimal reliance on external systems or human involvement. An autonomous system would monitor for incapacitation based primarily on measurement of pilot psychophysiological markers and performance markers. In addition, the pilot will be able to manually enable the redundancy system at any time, based on self-assessment of health. If a potential incapacitation is identified autonomously, the pilot will be requested to perform some action if he wishes to reject the warning. If the pilot fails to do so, minimization of a cost function combined with a database of nearby runways and their CAT rating determines the optimal runway. The optimization will be performed within the FMS, which will determine the route based on standard airways. At the moment an incapacitation is verified to be true, ATC is alerted autonomously through multiple existing communications channels. These communications will include the intended emergency runway and route. ATC will ensure separation from other aircraft along the route, instructing aircraft to divert where necessary. The assumption is made that by 2020, GPS integrity and continuity issues preventing implementation of GPS for precision approach guidance will be resolved. If this is not the case, ILS should be relied on to provide precision guidance during landing. This is considered a reasonable option in the rare event of incapacitation. ILS failures or malfunctions are rare. In addition, it may be an option that cabin crew provides for the visual reference required by ICAO for currently existing ILS systems. Currently, ICAO defines that CATIII instrument landing systems must ensure ability for taxiing in zero visibility. That is the reason CATIII has not been certified anywhere in the world as of 2012. However, for incapacitation scenarios, taxiing in zero visibility would not be an essential function. Furthermore, according to Airbus, "approach success rate [for Category II/III operations] in actual in-line services is now nearly 100%" (Airbus, 2001). Therefore, it is assumed that for CATII or CATIII, even if there is no means (pilot) to verify the runway is in sight at the DH, the safety level would be sufficient for the rare case of incapacitation.

If such a cabin crew is allocated responsibility to verify the runway is in sight, a suitable interface should exist for the cabin crew to perform this task adequately. It goes without mention that simulator training would be necessary for the cabin crew to practice this role. ICAO strictly regulates the four elements of CATII/III operations; aircraft, airfield, operator, and flight crew. This will impact the feasibility of such an SPIR solution.

The advantages of this option are that the solution is almost entirely self-sufficient. There is a very limited reliance on external systems or human roles. The minimal number of elements in this concept limit the opportunity for failure, both within the elements and their interfacing. This solution requires no alterations to elements of the air transport system external to the flight deck, also avoiding reliance on remote control and the accompanying security related debate.

However, even this optimal SPIR concept has a number of weaknesses. The most challenging issues to solve are the topic of the following subsection.

11-1-4 Critical Functions

A number of key challenges are identified in providing the functions for a single pilot incapacitation redundancy concept. These challenges have a significant impact on the feasibility of such a concept. The challenges are a result of the following functional requirements; a. the requirement for seamless and near-instant take-over of primary flight functions and partially completed tasks from an incapacitated pilot; b. the difficulty in judging the security hazard which remote control take-over of passenger commercial aircraft presents in a world with increasing wireless connectedness; c. the need to keep humans in the loop, to use their unique skillset to solve for unanticipated situations; and d. the challenge in identifying incapacitations of various types, with sufficiently low miss rate, but without imposing new dangers through excessive false warnings.

Although psychological incapacitations contribute to up to half of incapacitations, these incapacitations will be extremely challenging to identify autonomously due to the human nature of the issue. Another potential challenge lays in identifying cardiovascular incapacitations, as the magnetic cockpit environment may interfere with sensors. These factors affect the monitoring for incapacitation by autonomous monitoring system. Another challenge related to autonomous monitoring is the setting of sensitivity thresholds for identifying a potential incapacitation, and the time allowed for the pilot to reject automatic take-over. This leads to the conclusion that with current technology, humans are still best adept to instantly determine the health of another human. And yet, for the function of taking over the primary flight tasks, a human would only be better than automation if that human has received sufficient recent training.

The reasons to avoid remote control take-over are due to the security issues, the extensive challenges and costs of introducing such a system on large scale. The fact that due to communications delays the immediate and seamless aviating task may very likely still have to be performed from on-board. One option is to allocate the monitoring for incapacitation to a human, and allocate the primary flight functions to automation. For example, a cabin crew member could sit with the pilot in the flight deck during critical flight phases, and perform the call-out SOPs as takes place today. In the event of take-off, or in landing using ILS guidance equipment, the monitoring crew member may only require a big red button to hit if the pilot fails to re-call a speed, upon which automation would take over. With fly-by-wire primary flight controls, it should be no problem to disable the pilot primary control inputs, to prevent unwanted commands from an incapacitated pilot slouching on the controls. Cabin crew could still prevent the incapacitated pilot from making erroneous commands just as occurs today.

A final matter to restate is that the two functions of incapacitation verfication and recovery of immediate aircraft control present a design trade-off. Control must be taken over swiftly in case of a true identified incapacitation, and yet no new dangerous situations should be created by taking over control without a sound verification that the pilot is indeed incapacitated. The design challenge of setting the two thresholds; a. incapacitation identified (at which point the pilot is requested to react if OK); and b. incapacitation verified (at which point aircraft control is taken over, and primary pilot control inputs are neglected to prevent erroneous commands from an incapacitated pilot). The optimal thresholds depend largely on the urgency to recover the aircraft (hence phase of flight), and on the risk associated with disturbing the pilot with false incapacitation warnings. An incapacitated pilot presents the greatest risk during landing, meaning control take-over must occur as quickly as possible. And yet during landing the pilot WL is high, meaning the pilot may need more time to reject a false incapacitation warning. Clearly, this presents a key design challenge, which impacts the effectiveness of the incapacitation redundancy system, but also the degree to which new failure modes are introduced.

It has been aimed to devise a concept that would provide single pilot incapacitation redundancy for all flight phases. If redundancy were to be required exclusively during the non-critical flight phases, which make up most of total flight time, the design problem would be much simpler. It is suggested that a redundancy solution should function differently depending on the flight phase. It is recommended that during critical flight phases, various concepts are combined to result in a most versatile solution.

The following section presents a future flight deck concept in which these challenges would no longer exist. The concept also simplifies the redundancy problem, as number of dimensions that characterise the range of possibly occurring incapacitation scenarios are reduced.

11-2 Incapacitation Redundancy and the Hypothetical Future SPFD

In the previous section, a number of concepts were described that could provide redundancy for the functions provided by the pilot, in case the single pilot were to be medically incapacitated. The result is that even the optimal concept presents a number of challenges that would be so complex to solve, it may not be feasible by 2020. It is considered here, how these issues might be solved by a particular future SPFD concept. In particular, this section looks at a flight deck in which the role of the single pilot is even more that of a supervisor. In this FD, the entire flight would be routinely performed on autopilot; the pilot would only be present to solve technical issues on board, and control the aircraft manually if required.

In this concept, the flight route would be split up into a number of stages. The FMS would be programmed in conjunction with the auto-pilot to complete just one stage, and land immediately after that stage at a specific runway. If the end of that flight stage is about to be reached without an incapacitation, the pilot will initiate the succeeding flight stage. For example, when taking off, the FMS is be programmed to initiate a short climb after take-off and return shortly after to land. If the take-off would take place without an incapacitation, the pilot would command the autopilot to fly the succeeding stage of the flight, again programming it to land at a suitable pre-specified alternative airport immediately after that flight leg. Hence, if an incapacitation would occur, the aircraft would immediately land at the first suitable airport, chosen by the pilot. If no incapacitation would occur, the pilot would initiate the succeeding stage to be flown, again on autopilot. This cycle would repeat until the flight is either completed without incapacitation, or in rare cases is cut short by landing at an airport along the way due to an incapacitation. Of course, the pilot should be warned when the end of a flight stage draws near.

Potentially, the pilot might control the aircraft manually, unless diverging too far from the planned flight path. Automation could then take over control, as the deviation might indicate an incapacitation has occurred. It should be possible for the pilot to disable such protection so the pilot can operate the aircraft freely if unanticipated situations so require. However, similar protection systems have been prone to be routinely disabled by operators, yielding them ineffective for their purpose. Thus, some measures should exist to prevent routine disabling, such as alerting of the airline in the event of disabling.

The feasibility of this concept is challenged today due to the frequency of ATC requests to adjust the flight route. However, in a future ATS where four dimensional trajectory planning is the norm, interruptions from ATC may become rare. In that case, this concept of operation in short stages could even be integrated into the planning of trajectories. Possibly, each contingency landing trajectory at the end of any stage could even be analysed ahead of time to minimize collision risk with other aircraft.

This section has presented a concept for SPCO that would simplify the challenge of providing incapacitation redundancy. Although this method of flying might not be very appealing to pilots, the concept does present a solution to SPIR that is realizable even today. In fact, the basic concept of SPCO (operating an aircraft without a work companion) may not be very appealing to start with. This is however not the topic of this research.

11-2-1 Critical Functions now Provided or Obsolete

The feasibility of this hypothetical SPFD concept from the perspective of incapacitation redundancy can be verified by considering the Functional Decomposition (Figure 11-1). The functions that presented to be a challenge to solve for the scenario-SPFD, would mostly be solved if the FD was changed as described in Section 11-2.

The *Monitor for Incapacitation* would be provided by the pilot's failure to initiate the succeeding flight stage.

The *Verify Incapacitation is True* functionality becomes more simple, as the urgency is removed because a suitable autopilot mode is enabled by default. The pilot is simply warned and requested to react if the flight stage is coming to an end; no reaction means an incapacitation is assumed.

The *Recover Immediate Aircraft Control* function becomes obsolete, as the aircraft is not permitted to deviate from the planned route and flight conditions in the first place.

The *Choose Runway and Route* function is solved. This task has been added to the *Former Pilot Functions* when programming the stage. Clearly, the pilot should be required to program the next stage complete with descent and landing before being permitted to override the descent and landing of the current stage.

The *Aviate and Navigate to Airport* function would be provided by the automation, as instructed by the pilot prior to incapacitation. It is assumed that no failures occur in the automation, and that no adjustments are requested by ATC, as the aircraft is given priority.

The *Approach and Land Safely* functionality is assumed to be taken care of, as the autopilot would simply continue to land as programmed by the pilot. Because current A320 aircraft are already to land entirely on autopilot in normal circumstances, this should function fine in the rare case of an incapacitation.

Separation Assurance would still be provided by ATC just as occurs today. In the rare case an aircraft is nearing the end of a flight stage and the pilot is unresponsive to the warning from the FMS, a mayday message should be communicated to ATC some minutes before the pre-programmed descent and landing are initiated. Cabin crew should be alerted to check on the pilot. The message to ATC should include details of the planned route, runway and timing. Meanwhile ATC would have sufficient time to clear the airspace, providing separation.

The situation might occur in which the pilot becomes incapacitated midway a flight stage. This could remain unknown to the aircraft systems, cabin crew, and ATC until the end of the stage draws near. In this case, the separation assurance function would be provided by the mandatory on-board ACAS, just as would be today. If the ACAS must initiate an avoidance manoeuvre, the fact that the pilot has not responded to the ACAS traffic alerts would indicate that the pilot is incapacitated. ATC and cabin crew should then be alerted just as described above. ATC can then proceed to provide separation assurance during the descent and landing.

The *Pilot Retake Control* functionality can be to implemented at a later stage in design through an appropriate interface.

The complexities illustrated in Section 11-1-4 are overcome. This method of operating commercial passenger aircraft by a single pilot would allow seamless and safe continuation of flight in case of an incapacitation. Remote take-over would not be necessary; avoiding the risk of remote hijacking. The likelihood is assumed to be extremely difficult to estimate. The severity of the worst-case scenario (in which all equiped airborne aircraft are simultaneously threatened) would be catastrophic. The threshold problem, of how to reliably identify an incapacitation, without too many false identifications is solved. The seamless take-over problem, requiring awareness of the pilot's previous intentions and partly completed tasks is solved. Simultaneously, this concept avoids reliance on cabin crew with limited training and practice to perform safety critical functions. Finally, humans are kept in the loop; the emergency runway and route have been programmed by the pilot who will have checked for obvious hazards on this route.

11-2-2 Reduced Diversity of Potential Incapacitation Scenarios

The hypothetical SPFD concept allows the variety of possibly occurring incapacitation scenarios to be reduced. For instance, the same concept would function regardless of flight phase. The requirements of a SPIR solution are simplified as a result. The dimensions identified in Section 10-6 to characterize the potentially occurring scenarios that are simplified are:

- Flight phase: the same concept would function, regardless of the flight phase during which incapacitation occurs.
- Automation mode enabled: The mode of automation would always be suited to continue the flight until safe landing is completed.
- Interrupted pilot tasks, decisions, and commands: If the pilot provides a supervisory role, this is highly unlikely, unless other failures already exist, which is unlikely and has been assumed to be outside the research scope.
- Type of medical incapacitation: This concept would ensure redundancy for the essential pilot tasks no matter the type of medical incapacitation.
- Diagnostic test outcome for incapacitation detection: A false incapacitation identification is unlikely to occur, unless the pilot is by some other means unable to reject the warning. In this system, high workload would not be a major cause of failing to reject a false alarm, as the pilot would have sufficient time at the end of a stage. Furthermore, if the workload is high, this most likely means the pilot is actively interacting with FD systems. Such interactions could be used to determine the pilot is in good health. Therefore, false incapacitation detection appears highly unlikely. An incapacitation cannot go undiagnosed for a longer time-span than that between each flight stage. The length of a flight stage is a variable to be specified upon detailed design. Furthermore, flight stages could be planned so as not to end during a period of high pilot workload.

The findings have led to a concept of operations that overcomes the challenge of incapacitation, whereby the HMI of the single pilot aircraft may be more similar to a UAV HMI; controlled by means of higher level commands. The aircraft and flight deck would be fully autonomous and self-sufficient, yet offer *openings* to the internal workings functioning for the pilot to make repairs, reset systems while in the air, or take over manual control. A major challenge lies in the design of a Human Machine Interface that would facilitate the pilot in trouble-shooting and work-arounds in case of unanticipated situations or system failures which the autopilot cannot resolve. It should be said that the concept discussed here does not overcome the other technical challenges to SPCO of WL, SA, or PM.

It is a possibility that the crew reduction would continue in future years such that single pilot operations are skipped, and commercial flights are actually operated fully autonomously. Worthy of note is that the extent of research towards UAS far outweighs the research towards SPCO. Hence, it is not an unrealistic expectation that the first form of SPCO might consist of fully autonomous passenger carrying UAS, but with a human pilot or technical specialist on-board for unanticipated situations. A critical factor to the success would be the ability for the on-board technical specialist to access the internals of hardware and software, or even to bail out the aircraft in some other way.

This section has explored a hypothetical future SPFD concept for SPCO. The concept would require only limited alterations to conventional multi-crew FDs, to ensure the aircraft would be landed safely in case the single pilot becomes incapacitated. The functions required of a SPIR solution identified in the previous chapter would be feasibly solved. In this SPFD the pilot assumes the role of supervisor, directing the autopilot in sets of commands for finite stages of any flight. If an incapacitation were to occur, the FMS would in conjunction with autopilot, alert cabin crew, alert ATC, and subsequently descend and land precisely as the pilot directed prior to completing the previous flight stage.

11-3 Conclusions Incapacitation Redundancy Concepts

This chapter has presented the functional requirements that SPIR solutions must meet, and shortly discussed the options how each function could be fulfilled. The purpose was to demonstrate which functions are the most difficult to provide, and to relate this back to SPCO or a SPFD. Figure 11-1 illustrates the functions to be performed to achieve the mission statement, which is to land the aircraft safely in the event an incapacitation occurs during any phase of flight. The research of Part 2 has resulted in an improved understanding of the issues resulting from SP incapacitation; new insights into how redundancy for incapacitation might be provided for SPCO; and an understanding of the requirements on a SPFD as a result of the necessity for incapacitation redundancy. As found and explained in Parts 1A and 1B, incapacitation redundancy is a necessity for SPCO in order to meet target aviation safety levels.

An optimal concept for incapacitation redundancy was described, whereby an autonomous sensory system would monitor for incapacitation, together with self-monitoring of the pilot's own state. In case of a detected incapacitation, the pilot would be consulted prior to the enabling of autopilot take-over. The FMS would run an optimization algorithm combined with a database of airports, to determine the most suitable airport (with CATII/III ILS).

The conclusion was that each concept, including the optimal concept, would be very challenging to realize due to the following issues; a. the requirement for seamless and near-instant take-over of primary flight functions and partially completed tasks from an incapacitated pilot; b. the difficulty in judging the security hazard which remote control take-over of passenger commercial aircraft presents in a world with increasing wireless connectedness; c. the need to keep humans in the loop, to use their unique skillset to solve for unanticipated situations; and d. the challenge in identifying incapacitations of various types with near immediacy to prevent deterioration of flight conditions, yet achieve a sufficiently low miss rate so that no new dangers are created through excessive false warnings.

These design challenges are further complicated by the large variation in possible scenarios, as identified in Section 10-6. For instance, the actions to be performed to land the aircraft would vary according to the flight phase when the incapacitation sets on, and the tasks partially completed by the pilot. Each separate function is greatly complicated by the requirement to provide redundancy for a wide variety of situations, even when excluding additional failures from the scope. Taking these obstacles into account, a concept for a future hypothetical SPFD has been presented in which these obstacles would be overcome. In this SPFD concept the pilot would program successive short flight stages into the FMS, to be operated on autopilot. An autonomous landing would be programmed at the end of each stage at a suitable airport and via a suitable route. When the aircraft nears the end of a stage, the pilot is requested to initiate the succeeding new stage if he is fit. If the pilot fails to react, an incapacitation is assumed and ATC contacted for separation assurance, and the aircraft will simply follow the route and landing as defined by the pilot. A benefit of this concept is that the urgency is removed from the incapacitation monitoring function; the aircraft flight conditions will not deteriorate because autopilot is always enabled.

This chapter has demonstrated that the design of a SPIR solution for a FD similar to current multi-crew FDs, would be a challenging engineering task to fulfill. The cause is the great variation in possible scenarios. As a result, the automation must have a certain awareness of what the pilot was, is, and will be doing, in order to be prepared to take over control if an incapacitation would occur. A worthwhile topic for further study is to explore the ways in which automation could be made aware of the intentions of the pilot. For instance, by introducing SOPs such that the pilot must verbalize all actions and decisions, voice recognition could be used to develop an awareness of the pilot's intentions. In this way, it would be easier to take over the aircraft in case of incapacitation, as the automation is aware of the correct flight condition. Perhaps the actual actions of the pilot could be compared to his intended actions, as a measure to detect incapacitation. Once again, the SPFD concept operated in stages using autopilot, overcomes this issue by always using full autopilot.

Chapter 12

Conclusions and Recommendations

This thesis has uncovered and condensed the technical challenges that obstruct the realization of Single Pilot Commercial Operations. At the commencement of this research, existing literature on SPCO was scattered. Preliminary research indicated no solid research dialogue on the subject exists. Knowing that more crew is not per se safer, the author was intrigued by the scarcity of research towards SPCO. The possibility that with sufficient research SPCO might one day offer safer aviation has motivated the author to investigate the technical hurdles obstructing the realization of safe SPCO. This research is unique by the clear and systematic method in which the issues challenging SPCO have been uncovered and condensed to a comprehensive and comprehendible report. Throughout the research, a focus was laid on the technical challenges to SPCO; those challenges related to safety. Because very limited prior research existed on the topic, information was gathered in as broad a sense as possible. In doing so, a complete foundation was laid that clarifies the technical challenges to SPCO and may foster original research on the topic. The research was carried out in three phases. The first phase looked at the past and present, through analysis of aviation regulations, the history of crew reductions, and the context of aviation. The second phase explored the current technical challenges and potential developments that may help to overcome these challenges. Finally, the third phase explored the challenge of providing single pilot redundancy for the rare case of incapacitation, through determining the top level functional requirements and possible means to fulfil these functions.

Part 1A of this report has presented the findings of phase one, concerning the current context of aviation; historical evolution of FD and crew size; and current and past regulations pertaining to crew size. Analysis resulted in the finding that previous crew changes have been made possible through new technology and improved understanding of human factors. Each crew reduction was found to be paralleled with a redistribution of tasks across humans and automation, both on-board and off-board, to enable the crew reduction. In 1981 an impartial US presidential task-force (assigned to settle this dispute between Boeing engineers and pilot unions) determined that two-man crews were indeed safer than three-man crews. This is significant, because it illustrates that; a. more crew is not by definition safer; and b. crew size is certainly impacted by non-technical factors. In comparing drivers of flight risk to the regulatory criterion defining minimum legal crew size, it was found that the regulations are founded on an out-dated assumption; the assumption that flight risk is per se proportional to aircraft mass. The finding was that the current aviation environment (including design, certification, and operations) is oriented heavily towards multi-crew flight. As a result, high uncertainty and costs associated with SPCO research and operations discourage such investments. However, the developments of commercial UAS and revision of regulations suggest this atmosphere towards unconventional innovations is undergoing change.

Based on the insights gained of the past and present situation, the goal of research phase two (report Part 1B) was the identification of the technical challenges to SPCO. Over successive brainstorming and iterative research, a comprehensive list of all potential factors impacted by, or impacting on crew size, was formulated. Analysis of the listed items initially resulted in additional issues to consider, until the main issues were identified and only minor or insignificant issues turned up. After some iterations an order emerged; much akin to a hub-and-spoke model. At the center, the four predominant technical challenges of excessive workload, insufficient situational awareness and the necessity for peer performance monitoring; and somewhat isolated, the risk of pilot incapacitation. On the spokes surrounding the hubs were explicit matters such as checklist related issues, the alarm problem, and automation surprise (such as unobserved automation mode changes). Flight crews in current commercial flight decks are primarily present for when non-normal conditions arise; in which a single pilot would quickly be overwhelmed. A significant yet less tangible challenge to SPCO is that of pilot training and specifically learning on the job. In removing one pilot from the cockpit, the mechanisms for learning and self-reflection as a result of feedback from one's peers, are largely removed. This topic has received relatively little attention in this work, and deserves greater research. A number of developments were come across that might facilitate the road ahead for SPCO, in aiding to overcome the identified technical challenges. Advances in ATM, developments towards measurement of Operator Functional State for Adaptive Automation, and advances in real-time aircraft health monitoring may help to overcome the SA, WL, PF, and incapacitation challenges through enabling a redistribution of tasks both within and beyond the flight deck. Findings of Part 1B suggest that SPCO may be feasible by 2020, depending on progress in the areas stated above. Literature agrees that the incapacitation rate of commercial airline pilots is approximately 4e-7 per flight hour; which exceeds the FAA's maximum acceptable frequency of occurrence of 1e-9 (per flight) for any failure condition that would prevent the continued safe flight and landing of an airplane. The possible means of incapacitation detection were discussed; detection of psychological incapacitation is expected to be especially challenging.

Part 2 of this thesis has presented the findings of research phase three, in which the feasibility of achieving single pilot incapacitation redundancy was analysed. A flight scenario analysis and functional analysis were performed to determine the essential functions to be provided in the event the single pilot becomes incapacitated. The key requirements are the seamless and immediate recovery of primary aircraft control. It turned out that the challenge in achieving this is mostly a result of the great variation of potentially occurring situations. To build on this observation, a finite set of dimensions was isolated which could be used to describe the vast majority of incapacitation scenarios. Insights from the scenario analysis, the functional analysis, and the said dimensions were combined to form a Functional Decomposition capturing the essential functions for incapacitation redundancy. To provide true incapacitation redundancy, the solution must be able to continue safe flight and land the aircraft regardless of; flight phase, automation employed, the type of incapacitation, and the occurrence of falsely detected incapacitations. A key factor driving the success of such a system is the automation's *awareness* of the pilot's intentions at each moment in time, so that automation can take over immediately and seamlessly. The immediacy presented another challenge; rapid identification of incapacitation is a crucial factor impacting the overall feasibility of SPIR concepts. Based on this and other critical factors, a SPCO conceptual FD was proposed in which these critical factors would be overcome. In this concept, the pilot would pre-program an entirely autonomous flight in short stages, with a fully autonomous premature landing planned at the end of each stage. Should the pilot not react to a warning towards the end of a flight stage, automation would assume an incapacitated pilot and continue with the pre-programmed landing. It is a significant finding that such reorganization of the flight deck can greatly reduce the complexities of ensuring pilot redundancy; one of the predominant challenges to SPCO. It must be noted that in this way, the aircraft would land itself in case of an incapacitation, so long as no additional failures arise that on-board automation cannot resolve. An assumption was that ATC would manage separation in case of an incapacitation caused aircraft descent.

This research has provided a foundation for further research towards SPCO. A challenge encountered in this research was the difficulty in identifying *if* and *why* SPCO cannot be as safe as multi-crew operations, without the existence of SPCO concepts. Due to the limited single pilot research, the identified challenges may partly be a projection of the challenges faced by multi-crew FD design. For this reason, it is suggested that various concepts for SPCO are designed and tested in simulators. Through the actual design phases of such concepts, unknown challenges to SPCO are likely to surface. A finding of this research was that to realize SPCO, alterations are needed both *within* and *outside* the FD. This is in agreement with the findings of (Harris, 2007). Harris found that efficiency gains can be achieved but only by viewing the FD within the greater context of the Air Transport System. In order to gain a better understanding of the factors outside the FD that should change, it is recommended that various concepts of operations are created, with alterations to systems outside the FD of varying degree. In this way, it could be better understood what changes and external support are most essential. At this stage, SPCO is at a development stage in which changes outside the flight deck will be difficult to justify and thus severely restricted. Nonetheless, the aviation atmosphere is heavily oriented towards multi-crew operations. A first step should be to build evidence of potential SPCO benefits. It is therefore suggested that succeeding SPCO research is aimed at devising and simulating specific concepts of operations. The emphasis should be on developing human factors understanding specific to single pilot operations, rather than developing a feasible solution straight away. For these concepts, much could be learned from military single pilot operations. By looking at particular concepts, SPCO benefits and explicit challenges may come to light that can help justify alterations outside the FD.

During the three phases of this research, some other topics for future research turned up. During the discovery of the technical challenges in phase two, it was found that the challenge of providing an alternative means for performance monitoring for SPCO is reason to investigate the remote monitoring of aircraft health. This might realistically contribute to safety in the future, if bandwidth and coverage of digital data connectivity is expanded. Modern aircraft record a great quantity of sensory data; far too much for the pilot to analyse in flight. Potentially, this could be autonomously monitored and supported by a remotely located team of experts *before* situations are able to deteriorate. Remote monitoring of aircraft (and pilot) health could relieve the pilot(s) of workload, increase situational awareness, and provide new means of performance monitoring all at once. A worthwhile topic of future study is the determination of what data should be transmitted, considering the constraints on telemetry. Remote performance monitoring could first be tested and improved in conjunction with multi-crew FDs.

The third research phase has identified some challenges specific to realizing Single Pilot Incapacitation Redundancy. A significant challenge was imposed by the requirement that aircraft systems should have an awareness of the pilot's intentions. This is necessary in order for automation to *know* when and how to recover the primary control of the aircraft. Thus, it would be worthwhile to invest further research efforts at context awareness of automation and the collaboration between humans and automation.

In the environment of aviation which is currently very much focused on multi-crew operations, there is a natural tendency to view a hypothetical SPFD as a multi-crew FD with one fewer pilot. And yet, multi-crew FD's are optimized for operation by two crew, not by one. One can then expect that the single pilot will run into trouble in such a FD. A challenge in considering single pilot operations lies in this natural tendency to use multi-crew analogies. To overcome this, the entire FD and certain external systems should be viewed as a blank canvas, so that the challenges to SPCO naturally arise during a design process from scratch for SPCO concepts. Therefore, the design and simulation of specific SPCO concepts should be a focus of following SPCO projects; benefits to SPCO may well arise as a result.

Appendix A

Divergent Research Phase Deliverable: Long-List; Factors Potentially Impacting Crew-size

Table A-1 shows the deliverable from the divergence phase; the list of most factors considered relevant to the feasibility of single pilot commercial operations. This list is based on the start of the research. It provides an indication of the research methodology, but is in no way a final deliverable of the research.

Table A-1: Longlist; research topics that turned up during divergent research phase

History of aviation and flight crew reductions
Future ATM
Aviation safety
Future communication systems
Automation developments
Aviation in a broader spectrum: general global trends
Similar sociotechnical work environments
Aviation policy makers and stakeholders
Theory on adoption of new technologies
Airframe manufacturers design philosophies
Certification & regulations
Human factors research
Airline management decisions
Potential new technologies in developing stage
Accident/incident reports, analysis, and institutions
Aviation medical research
Pilot incapacitation rates (cardiovascular diseases)
Military single pilot aircraft design
Threats to aviation security
Single Pilot Resource Management
Line Operations Safety Audit (LOSA, LOSA:SP)
Adaptive automation support
Operator Functional State
Cockpit call-outs
Cockpit alert threshold and audio vs. visual
Workload, Situation Awareness, and Human Machine Interaction
NextGen (next generation air traffic management)
SESAR
Distributed control
Teams and shared cognition, shared situational awareness
Single Pilot IFR approach
Decision making (errors)
Flight Fatigue
Very light jets
Checklists/monitoring
Hypoxia
Psychophysiological measurement
Wearable health monitoring systems
Auto-land systems
Digital Data-link
ADS-B and potential new avionics, display, and interfaces
Accident causation models
Human error models
Tunnel-in-the-sky, and synthetic vision systems
Redistribution of responsibilities aircrew and ATC
Cognitive Systems Engineering

Appendix B

Technology and Crew Reductions

Table B-1: Specific Technological Advancements and Corresponding Crew Reductions

Date	Specific Change	Flight Crew Size
1931	New legislation in US: co-pilot on all aircraft $>$ 15,000 lb, or $>$ 15 passengers	5
30's	Radio operator no longer needed over populated areas	4
1948	New legislation in US: FE on aircraft $>$ 80,000 lb (The 80,000 lb Rule)	4
50's	Navigator no longer needed over land (VOR beacons)	3
50's	Fewer FE tasks on jet aircraft; (fewer) jet engines; no inflight adjustment	3
1965	US 80,000 lb Rule revoked. FE no longer required on aircraft $>$ 80,000 lb	3
Late 60's	Navigator intercontinental flights no longer legal requirement; Inertial Navigation Systems (INS)	3
70's	Boeing 737 no FE; EICAS, EFIS and 2 CRT displays provide SA.	2
1982	Boeing 767 and 757 certified for two crew; resistance pilot unions overcome	2
1985	Boeing 747-400 now without FE	2
2003	Retirement Concorde; last modern commercial aircraft with FE (FE balanced 13 fuel tanks)	2

Appendix C

Operations Excluded from Part 119; Single Pilot Permitted

There are some flight operations to which part 119 of FARs do not apply. Provided the aircraft is certified for single pilot operations, the operations listed in this excerpt from the Federal Code of Regulations (FAA, 14 CFR Part 119) do not require two pilots (FAA, 2012d):

1. Student instruction
2. Nonstop sightseeing flights with less than 30 seats and less than 25 nautical miles from the departure airport
3. Ferry or training flights
4. Crop dusting or other agricultural operations
5. Banner towing
6. Aerial photography or surveying
7. Fire fighting
8. Powerline or pipeline patrol
9. Parachute operations on nonstop flights within 25 nautical miles from the departure airport
10. Fractional ownership in accordance with part 91, subpart K

Appendix D

Considered Alternative Methodology Part 2; Quantitative Risk Analysis

For the detailed single pilot incapacitation research of Part 2, it was initially intended to conduct a quantitative risk analysis. Ideally, a feasibility study of a single pilot incapacitation system would include a system safety analysis. The purpose of such an analysis is to determine the system robustness requirements that would result in an overall flight safety level equivalent to multi-crew operations. System robustness requirements define which potentially occurring situations the system must be capable of coping with.

The advantage of such an approach is that the likelihood of certain failures or certain hazards leading to accidents, can be compared quantitatively to the target safety levels. It has been previously shown that the rate of pilot incapacitation is too high to satisfy the target safety levels required for aircraft certification with a single pilot in current flight decks designs. However, it was hypothesized that a single pilot in combination with a system that could land the aircraft in case of incapacitation might achieve the same overall reliability. To achieve this, it must be considered which conditions the system must be able to cope with; hence, the required system robustness must be determined. Because the target safety levels of multi-crew flight decks are known, and the rate of incapacitation of pilots is known, the required system robustness might be derived based on the frequency of the most common events and hazards. However, a quantitative analysis was avoided due to the following drawbacks:

1. Humans are known to be poor at predicting the frequency of occurrence of very rare events. The results from quantitative analyses are not known with absolute certitude. For example, the battery situation of the 787 Dreamliner is one such example; where 2 failures occurred within 52,000 flight hours, even though the expected rate of failure was estimated at once in every million flight hours (check this) (ref). According to J. Stoop, aviation safety expert at Delft University of Technology, to counter the possibility of such ill-predictions the likelihood of any conceivable failure in safety critical systems such as aviation, should be considered to be one. Unfortunately that would render a quantitative analysis to identify robustness requirements worthless.

2. Secondly, quantitative data regarding the frequency of occurrence of particular events are often limited, and dependent on the overall system design. That is, a new system will introduce new failure modes, of which the likelihood can only be partially understood at its implementation.
3. Software failures (or malfunctions) are notoriously difficult to predict.
4. To adequately perform quantitative safety analyses, a multi-disciplinary team of experts is usually required. Such a quantitative safety analysis is commonly performed at a more definite stage of a project.

Although a quantitative risk analysis would result in an explicit list of robustness requirements, due to the mentioned drawbacks such an analysis was avoided. To make the scope of this research manageable it was decided to focus on the scenario in which all conditions are ideal, except for the incapacitated pilot, to understand the basic requirements for a redundancy system. For completeness, a qualitative analysis of the most likely risks that could occur on top of the incapacitated single pilot is provided in Appendix E.

As explained in the main body of this report, it appears that the historical frequency of incapacitation occurrence makes incapacitation an *improbable* failure condition. Flight crews are not required to be capable of handling adverse operating conditions in the event of improbable failure conditions. Therefore, this would imply that a single pilot aircraft encountering such a failure condition (incapacitation) would not be required to cope with adverse operating conditions either. In other words, in the event of an incapacitation on-board SPCO, the incapacitation redundancy system would not need to be capable of coping with adverse operating conditions.

The legal soundness of this logic rests on the precise definitions adhered. Due to slight variations in terminology, it is possible this reasoning may not hold up under legal scrutiny. If this reasoning were to hold up, quantitative risk analysis would not be a requirement to determine the (legal) robustness requirements of an incapacitation redundancy system.

Appendix E

Factors Impacting the Outcome of Aviation Emergency Situations

To limit the research scope of Part 2, coping with additional failures has been excluded from the requirements for the SPCO pilot redundancy concepts. As reference for further study, this appendix lists the factors most likely to impact the “progress and outcome of different categories of [aviation] emergency”, as per the CAA ((SRG, 2005, p. 19)[1].

- Fire or smoke
- Loss of pressurization
- Failure of all engines
- Engine failure - take-off, climb, cruise, or descent
- Rejected take-off - High speed or low speed
- Landing gear failure
- Hydraulic failures
- Total (or nearly total) electrics failure
- Birdstrike
- Control problems
- Fuel shortage
- Icing
- Radio failure

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[1] Only the most relevant factors to incapacitation emergencies are listed here.

Appendix F

Functional Breakdown used to Research the SPIR Subfunctions

An initial Functional Breakdown (FB), depicted in Figure F-1, was formulated at the very start of the research for Part 2. This FB was created merely to aid in the requirements identification for incapacitation redundancy for SPCO. Each of the subfunctions in the FB were researched in some depth to determine if that subfunction would present any significant challenge to solve. In this way, the incapacitation problem was better understood. Finally, the insights gained were used in the formulation of the Functional Decomposition (Section 11-1-1). The Functional Decomposition is the final representation of the required functions of an SPIR solution.

Because the FB included in this appendix was only an initial research tool, there are some drawbacks. For instance, the subfunctions include too much detail, directing the resulting SPIR solution in a particular direction. This was adjusted for the Functional Decompositions, which therefore is a higher-level generic representation of the required functions. The FB is included to clarify the research process to the interested reader.

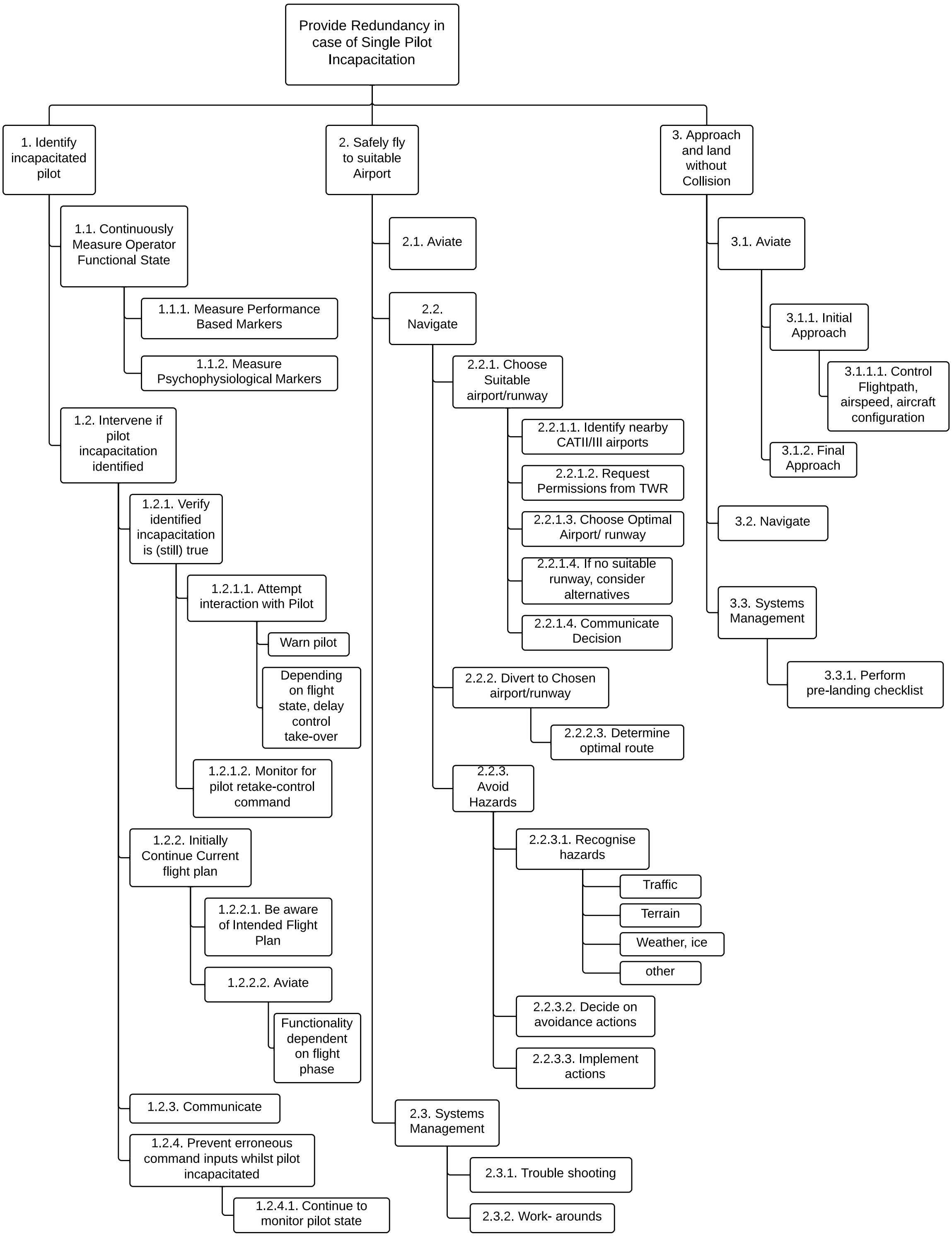

Figure F-1: Functional Breakdown

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