System Architecture for Single-Pilot Aircraft in Commercial Air Transport Operations

by

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ABSTRACT

Commercial flight operations have seen the consistent reduction of flight crew from five to two over the past several decades. As technology improves and airplanes become increasingly capable of flying themselves, this trend of crew reduction can be expected to continue. Single pilot operations in commercial air transport presents a range of benefits and challenges, some of which are explored in this thesis. While there has been some discussion of the concept of having a single pilot operate a complex aircraft, including an announcement by a regional jet manufacturer of their intent to realize the concept in the first half of the next decade, it is seen that there is a need to define architectures and compare them in different operational contexts.

This examination of architectures is conducted by identifying high level concepts or architectural decisions mentioned in the literature reviewed thus far, and creating an architectural space containing the possible constrained combinations of architectural divisions. The architectural space is represented as a safety versus cost trade space, wherein different architectural combinations are compared against present day operations. An attempt is also made to identify possible off nominal situations and the ability of the different architectures to deal with them. Safety is studied primarily as a function of pilot workload, which is identified by studying the movement of flight operations processes from the first officer, who is eliminated. Cost in this context is regarded as a combination of acquisition costs and operating costs. The former is quantified by identifying likely changes in system complexity, while the latter is a combination of crew and new infrastructure costs.

Moving to SPO requires taking into account the operating context. The analysis indicates that different classes of aircraft – widebodies, narrowbodies, and regional jets – have different levels of benefits and costs in moving to SPO. Capabilities of automation needs to improve drastically before the second human in the flight deck can be replaced, and this is borne out by the dominance of human centered concepts in the trade space. The analysis also indicates that regional aircraft may be prime candidates to move to SPO first, as most regional architectures generate positive savings.

Thesis Supervisor: Bruce Cameron
Title: Director, System Architecture Lab, MIT
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I would also like to thank all the faculty members whom I’ve had the privilege of being taught by, your advice and help was invaluable. I would especially like to thank the SDM teaching team of Prof. Oli DeWeck, Bruce Cameron, Bryan Moser and Qi Hommes for guiding us through the core curriculum. I would also like to thank John Helferich for being an amazing TA for SDM core, his entertaining recitations and ability to distill complex concepts into easy-to-understand lessons is unparalleled. Additionally, I would like to thank Prof. Chuck Oman and Mr. Brian Nield for the incredible experience that was 16.767 – I consider myself doubly lucky to have been able to undergo that experience both as student and TA. And finally, I must mention Prof. Arnold Barnett, to whom I owe the privilege of having been able to sit in on the finest lecture I have ever attended - his guest lecture on airline safety statistics for 16.71.

I would like to thank and acknowledge Mr. Parag Trivedi of General Electric, formerly Design Lead for Honeywell in India, for his support, encouragement and contributions to my aviation career, for having taken a chance on me by giving me my first job, and backing me up all the way through to the point where I achieved my dream of becoming a pilot.

And finally, I would like to acknowledge the hugely competent SDM cohort, their company and friendship were a big part of my journey here towards bettering myself. The most important lessons I learnt at MIT came from my friends in the cohort, and I consider myself lucky to have been part of a such a diverse group. I thank them, too, for accommodating my idiosyncrasies, accepting me as a friend, and inspiring me to do more.
DEDICATION

I dedicate this thesis to my parents, Asokan and Jayasree, to whom I owe everything. They have been my pillars of support my entire life, and have constantly encouraged, inspired and taught me by example to push the limits of my abilities. Without you being such amazing parents, I would have settled for far less, never knowing I was capable of so much more. I love you both.

I would also like to dedicate this thesis to my brother Anand, for the guidance and common sense he provided on those days I needed them the most. He has often believed in me on days I didn’t myself.

And finally, I would like to dedicate this thesis to my long-suffering friends Vijay, George, and Nithin, for their friendship and laughs along the way.
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<th>Description</th>
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<tbody>
<tr>
<td>ACARS</td>
<td>Aircraft Communication, Addressing and Reporting System</td>
</tr>
<tr>
<td>ADS-B</td>
<td>Automatic Dependent Surveillance - Broadcast</td>
</tr>
<tr>
<td>ATC</td>
<td>Air Traffic Control(ler)</td>
</tr>
<tr>
<td>ATM</td>
<td>Air Traffic Management</td>
</tr>
<tr>
<td>ATP</td>
<td>Air Transport Pilot</td>
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<tr>
<td>CDTI</td>
<td>Cockpit Display of Traffic Information</td>
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<tr>
<td>CPDLC</td>
<td>Controller Pilot DataLink Communication</td>
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<tr>
<td>CRM</td>
<td>Crew Resource Management</td>
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<tr>
<td>Dx</td>
<td>Flight Dispatch</td>
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<tr>
<td>ECAM</td>
<td>Electronic Centralized Aircraft Monitoring</td>
</tr>
<tr>
<td>EFB</td>
<td>Electronic Flight Bag</td>
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<tr>
<td>EICAS</td>
<td>Engine Indication and Crew Alerting System</td>
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<tr>
<td>ETOPS</td>
<td>Extended-range Twin-engine Operational Performance Standards</td>
</tr>
<tr>
<td>EVS</td>
<td>Enhanced Vision System</td>
</tr>
<tr>
<td>F/A</td>
<td>Flight Attendant</td>
</tr>
<tr>
<td>F/O</td>
<td>First Officer</td>
</tr>
<tr>
<td>FAA</td>
<td>Federal Aviation Administration</td>
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<tr>
<td>FDTL</td>
<td>Flight Duty Time Limitations</td>
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<tr>
<td>FMS</td>
<td>Flight Management System</td>
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<tr>
<td>GA</td>
<td>General Aviation</td>
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<tr>
<td>HITS</td>
<td>Highway In The Sky</td>
</tr>
<tr>
<td>ILS</td>
<td>Instrument Landing System</td>
</tr>
<tr>
<td>LCC</td>
<td>Low Cost Carrier (e.g., Southwest Airlines)</td>
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<tr>
<td>LNAV</td>
<td>Lateral Navigation</td>
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<tr>
<td>Mx</td>
<td>Maintenance</td>
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<tr>
<td>NAS</td>
<td>National Airspace System</td>
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<td>Pax</td>
<td>Passengers</td>
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<td>Abbreviation</td>
<td>Description</td>
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<td>---------------------------------------</td>
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<tr>
<td>PF</td>
<td>Pilot Flying</td>
</tr>
<tr>
<td>PNF/PM</td>
<td>Pilot Not Flying / Pilot Monitoring</td>
</tr>
<tr>
<td>RNAV</td>
<td>Area Navigation</td>
</tr>
<tr>
<td>RNP</td>
<td>Required Navigational Performance</td>
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<tr>
<td>SOP</td>
<td>Standard Operating Procedure</td>
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<tr>
<td>SPO</td>
<td>Single Pilot Operations</td>
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<tr>
<td>SVS</td>
<td>Synthetic Vision System</td>
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<tr>
<td>TA/RA</td>
<td>Traffic Advisory/Resolution Advisory</td>
</tr>
<tr>
<td>TCAS</td>
<td>Traffic and Collision Avoidance System</td>
</tr>
<tr>
<td>UAV</td>
<td>Unmanned Aerial Vehicle</td>
</tr>
<tr>
<td>UAS</td>
<td>Unmanned Aircraft System</td>
</tr>
<tr>
<td>VNAV</td>
<td>Vertical Navigation</td>
</tr>
<tr>
<td>Wx</td>
<td>Weather</td>
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<td>XPDR</td>
<td>Transponder</td>
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1. INTRODUCTION TO THE PROBLEM

1.1 Technological Progress and De-crewing

Despite high profile crashes and incidents in recent years (Air France 447, Malaysian 370 and 17, Germanwings 9525, Metrojet 9628 etc) aviation safety has progressively improved over the years. 2015 saw the lowest number of accidents (including hijacking and terrorism) in aviation history, while fatalities were also on a downward trend (Figure 1, Figure 1.1). Improvements in safety have also happened alongside a parallel trend of increased use of technologies and automation, as well as a reduction in the number of flight crew.

While early aircraft were simple enough for one or two people to operate, increasing technical complexity led to the addition of a flight engineer position (starting with some early flying boats, and subsequently the Boeing 377 amongst land based aircraft). With the increase in range transited by aircraft and improvements in radio communication, the flight deck saw the addition of the navigator and radio operator positions (sometimes combined into one). In Soviet origin large airplanes (An-12, An-22, An124, Il-62etc) there were often as many as six flight deck crew due to a combination of requirements
: English proficiency for the radio operator, complexity of systems requiring two flight engineers, and industrial or labour practices preventing the reduction of crew.

With the advent of the glass cockpit and increasing levels of automation within the flight deck, there has been a progressive reduction of flight crew required to operate an aircraft. The radio operator position was the first to disappear, followed by the navigator, and finally the flight engineer. The change was led initially by narrowbody aircraft like the 737 and the DC-9, with larger airplanes like the 747, 757/767 and A300 catching up later. Improvements in flight deck system capability and automation have enabled a fewer number of crew members to perform these functions. The trend for increasing automation has arguably continued, with most airline pilots on modern aircraft engaging the autopilot immediately after takeoff, and taking back control only at the very last stages of landing. With technologies like RNP (Required Navigational Performance), today’s airplanes can fly sophisticated flight paths in four dimensional space with minimal pilot input, enabling automated flight into challenging airports and conditions.

Taking this progress of automation to its logical conclusion, some have predicted that pilotless passenger aircraft are maybe two decades away (Adler and Gellman 2012), while more pessimistic commentators suggest that it will happen in the next 100 years (W. W. Johnson et al. 2013). While that may or may not be the case, this thesis looks at the scenario of increased automation where a single pilot is adequate for the safe operation of the aircraft. Manufacturers like Embraer of Brazil (Andrew Doyle 2010) have already made public announcements regarding their intent to offer aircraft with single pilot capabilities somewhere beyond 2020, in a reflection of the seriousness with which this concept is being viewed. It is also generally presumed that other manufacturers like Airbus and Boeing are evaluating the concept, though no public announcement has been made of the progress in research.

1.2 Reduction of Cockpit Costs

Labour costs are the highest component of a passenger airline’s total operating costs. In 3Q 2015, labour costs for American passenger airlines was 30.7% of its operating costs, compared to fuel costs which
were 18.9%. While fuel costs compare favourably with labour costs at present due to depressed oil prices, labour costs have in the past several years remained close to but below fuel costs. The labour force of an airline is broken down as shown in chart X and based on 2010 data, pilots and copilots made up 16.2% of the labour force employed by American passenger airlines. While they are lower in percentage terms especially when compared to administrative and passenger handling staff, they are

*Figure 2 Quarterly cost breakdown – Passenger Airline 3Q2015 (Airlines For America 2015)*
typically much higher paid in general. Flight deck crew on average earned $174,655 in the American passenger airline market in 2014, compared to the total average employee pay of $76,510 (MIT Airline Data Project 2014).
Further, pilots at low cost carriers in 2014 earned an average of $178,560 compared to the mainline average of $175,846 (MIT Airline Data Project 2014). While this does not take into account employee productivity and seniority mix at these airlines, it may well be argued that reducing the number of pilots may be the next frontier for cost reduction at LCCs. For instance, the average pilot wage at Virgin
America, a younger carrier, is $134,541 compared to $197,782 at Southwest which is much older. For LCCs, crew cost slowly drives up their cost base as the airline grows, and reducing the number of pilots may present an opportunity for significant savings. The announcement by Embraer (Andrew Doyle 2010) may certainly be viewed from this prism, since that company’s products are in service primarily with low cost and regional carriers, apart from business jet operators.

It must be noted here that SPO architectures will affect different types of airlines in different ways. For each airline, the actual cost reduction will need to factor in the average pay scale and seniority, the business model of the airline, the fleet and associated scope contracts, stage lengths and productivity (both aircraft and crew), and scheduling efficiency. Depending on the architecture, training costs, fleet acquisition costs, and other infrastructure costs (ground stations, for example) will affect the overall savings equation in different ways. Such downstream effects of different SPO architectures proposed need to be evaluated in detail by future studies dedicated to the economics of SPO. For aircraft with more than one type of use (pax, cargo, special missions), it would also be useful to quantify the benefits versus costs tradeoff of different architectures.

Another trend worthy of consideration when making the case for single pilot operations is the prospect of a pilot shortage reported in news articles over the past few years. While this is not an issue that has been the subject of widespread academic study there have been press articles from trade bodies and other stakeholders addressing it. One study conducted at the University of North Dakota (Higgins et al. 2013) found that the US alone faces a cumulative pilot shortage of 35,000 pilots compared to a cumulative demand for 100,000 pilots by the year 2031. A combination of low wages at the entry level, and tightening entry barriers in terms of experience (FAA 2013), have led to fewer people choosing commercial flying as a career option, it is argued. Universal adoption of single pilot operations in commercial air transport could help match supply and demand of pilots, or at least narrow the gap. Long term implications of this particular are outside the scope of this thesis. Conversely, there is also the possibility that SPO would lead to lower costs per seat-kilometer, which in turn can lower ticket costs and spur demand, increasing the number of flights and keeping the pilot requirement steady. While this
idea was proposed by Kopardekar (W. W. Johnson et al. 2013) at the NASA SPO technical interchange meeting, there is no evidence offered of this having been quantitatively established.

Given all of these factors, and given that all airlines have striven to reduce labour costs over time, single pilot operations can arguably be viewed favourably from the perspective of reduction of operating costs, provided that architectures are chosen carefully so as not to incur new additional costs that wipe out the marginal benefits.
1.3 Safety Considerations

As can be seen in the Figure 5 above, jet aircraft of the current generation and recent vintage are typically crewed by two pilots. The A300 (early versions) was the last aircraft introduced with a flight engineer position. Increasingly reliable systems made possible through newer technologies have also improved the safety of passenger aircraft, while managing an increase in complexity and capability (MD-11 is a bit of an outlier in this regard). The reduction in crew has been possible largely due to increasing levels of automation. Starting with rudimentary one-axis autopilots, automation is now capable of performing most of the tasks involved in flight, including very specific tasks requiring high accuracy and performance, for example RNAV approaches and autonomous Traffic Resolution maneuvers. The safety improvements
over time have happened due to the increasing reliability of aircraft subsystems (Harris 2007), as well as aviation's culture of safety where lessons learnt from mishaps are assessed thoroughly, disseminated widely, and assimilated quickly. Certifying airplanes for SPO will present a challenge in terms of safety and technology. In the history of reduced crew operations, it can be seen from Figure 6 that airplanes designed in the sixties had to undergo certification challenges similar to those that will be faced when moving to SPO. Boeing and Douglas successfully argued in the sixties that the B737-100 and DC-9 had systems that we sufficiently automated to allow them to be operated by two person crews, and proved that the workload faced by each of the two pilots was lesser than that faced by each member of a three person crew. Widebody aircraft, which were initially deemed too complex for two person operations, were eventually certified when Boeing successfully persuaded the FAA to allow two person operations on the B767. The key lesson in this regard is that regulatory factors must not be seen as an insurmountable challenge – certification instead should be seen as an imperfect tool that helps achieve safety (W. W. Johnson et al. 2013).

**Accidents by Primary Cause**


<table>
<thead>
<tr>
<th>Cause</th>
<th>Percent</th>
</tr>
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<tr>
<td>Flight Crew</td>
<td>64%</td>
</tr>
<tr>
<td>Airplane</td>
<td>19%</td>
</tr>
<tr>
<td>Weather</td>
<td>16%</td>
</tr>
<tr>
<td>Misc./Other</td>
<td>7%</td>
</tr>
<tr>
<td>Maintenance</td>
<td>5%</td>
</tr>
<tr>
<td>Airport/Air Traffic Control</td>
<td>8%</td>
</tr>
<tr>
<td>Total with known causes</td>
<td>126</td>
</tr>
<tr>
<td>Unknown or awaiting reports</td>
<td>50</td>
</tr>
<tr>
<td>Total</td>
<td>186</td>
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*As determined by the investigating authority. percent of accidents with known causes.

*Figure 6 Causal Factors in Aviation Accidents (Schutte et al. 2007)*
Along with the increase in automation and the reliability of onboard systems on modern aircraft, there is a correlated safety trend of note: actions by the crew account for 62% of the hull loss accidents in the decade between 1994 and 2003 (Schutte et al. 2007), and the trend has continued since then. Since human error is the biggest cause of accidents, proponents of unmanned passenger aircraft argue (Philip Bump 2013) that eliminating the pilot is the way forward for safer operations. Setting aside the merits of that argument, it must be noted that SPO presents a unique challenge wherein the number of humans available to make errors are reduced, yet the remaining human may now be even more error prone. As aviation progresses towards a fully autonomous future, the single pilot scenario offers challenges with regards to safety and automation. Single pilot aircraft will necessarily feature increased automation as it takes over at least some of the duties of one crewmember (Deutsch and Pew 2005), and the challenge of maintaining levels of workload at or below what a single crewmember experiences today will become important. In fact, going by precedent, that may be one of the yardsticks used by regulatory authorities in the certification path for SPO.

Increased automation will also need to address challenges of automation blindness – where the operator is not aware of what the system is doing at any given point in time – as well as skill degradation from relying on automation for extended periods of time (Chialastri 2012). A number of recent accidents – Air France 447, Indonesia Air Asia 8501, Asiana 214 are good examples – show a disturbing pattern of actions by the flight crew that would run contrary to what is taught as part of basic stick-and-rudder flight skills. All three cases also show that the crews were, at the very least, only partially aware of what the automation was doing. SPO may involve a change of role of the pilot towards being more of a manager of systems, and such architectures will need to find ways to prevent skill degradation, as well as improve the abilities of the pilot to respond when a failure does occur in flight.

SPO will also need to address the positive role played by collaboration between crew members in decision making, since this is bound to see fundamental changes depending on the SPO architecture chosen. For the past may decades, the concept of Crew Resource Management has been central to airline operations. It was introduced in the wake of accidents caused by human factors, especially notable ones like the collision between KLM and Pan Am B747s at Tenerife which led to the loss of 583
lives – the deadliest aircraft accident to date. The eagerness of the KLM captain to take off led him to deviate from procedures, and the authority gradient within the cockpit prevented the first officer from speaking up (Netherlands Aviation Safety Board 1978). In contrast, events of recent years like the US 1549 water landing in New York and the Qantas 32 uncontained engine failure on an A380, are often cited as examples of great CRM where the crew worked collaboratively to safely solve a potentially catastrophic in-flight problem. When only a single pilot is on board, the nature of decision making changes, especially in off-nominal scenarios. SPO architectures will need to consider this carefully, along with other non-trivial factors such as boredom on a long flight.

In summary, while safety has improved and the number of crew have decreased in decades past, SPO represents a unique challenge that needs to be handled with care to ensure these trends continue.

1.4 Research Objectives

This thesis aims to take an integrative approach towards designing a possible system architecture for a single pilot commercial transport aircraft. This is planned to be achieved by the following steps:

1. Literature Review: This stage will determine the current state of the research landscape involving single pilot operations. It will aim to look at new concepts proposed, as well as determining the state of the art for various subsystem level technologies that would be required in a single pilot aircraft (e.g., voice/speech recognition, checklist automation, etc).

2. Analysis of viability: In this chapter, the thesis will look at the commercial and safety pros and cons of single pilot aircraft at a high level, identifying key challenges ahead.

3. Defining a baseline: This chapter will deal with the definition of a baseline model against which the SPO architectures can be compared against. It will outline the methods and assumptions made in quantifying architectural characteristics.
4. Architecture decisions: Based on the literature review and secondary research, and incorporating reasonable assumptions of anticipated technological progress as well as current research trends in SPO, this section of the thesis will propose high level architectural decisions.

5. Analysis of concepts: The architectural decisions as defined in the previous chapter will be combined into various architectures, with logical constraints applied. This chapter of the thesis will analyze the architectures developed by comparing them on a cost versus safety tradespace.
2. LITERATURE REVIEW

The literature review for this thesis was conducted under three broad headings – building the case for SPO, Architectural Concepts and Analysis, and Safety. From the literature reviewed, it was seen that a mix of high-level and subsystem or function-focused studies related to SPO have been conducted. The NASA technical interchange meeting on SPO, for instance, has published its proceedings (W. W. Johnson et al. 2013) which contain high level conceptual directions and suggested research focus. Many studies have resulted from the direction set by this committee, and some of those have been covered in this literature review. The NASA committee, at a high level, also addresses the safety, human factors, and certification concerns and challenged that may be faced by SPO. There are also a few studies dealing with high level system modelling of single pilot operations. At a system level, the research landscape can be described as incomplete. There are no significant studies dealing with the business and operational impacts of SPO. It is important to understand that the operational context for SPO will vary between different types of operators – full service carriers, LCCs, cargo airlines, and charter operators will all have varying needs, and these have not been addressed as inputs to an architecture, nor have any direct comparisons of architectures been made. It is also noteworthy that even at the NASA SPO steering committee level, SPO appears to be defined only in terms of reducing the number of flight crew to one, without providing architectural context to the definition. While different means of achieving this is mentioned, not all of those possible architectures have been examined in detail. Also missing from the research landscape is the impact on and from second and third level architectural issues – for example crew scheduling, training, and other additional costs and complexity that may be incurred. This may be due to the fact that SPO is still at least one generation of aircraft away from being realized, but the point still stands that different architectures for different operators needs to be evaluated.
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<th>Title</th>
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<td><strong>Case Building</strong></td>
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<td>Strategies for managing risk in a changing aviation environment</td>
<td>Adler, Nicole ; Gellman, Aaron</td>
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<td>Single pilot IFR autopilot complexity/benefit tradeoff study</td>
<td>H. Bergeron</td>
<td>1963</td>
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<td>Single Pilot Commercial Aircraft Operation</td>
<td>Deutsch, Stephen; Pew, Richard W</td>
<td>2005</td>
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<td>A human-centered design agenda for the development of single crew operated commercial aircraft</td>
<td>Harris, Don</td>
<td>2007</td>
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<td>The Naturalistic Flight Deck System : An Integrated System Concept for Improved Single-Pilot Operations</td>
<td>Schutte, Paul C ; Goodrich, Kenneth H ; Cox, David E ; Jackson, E Bruce ; Palmer, Michael T ; Pope, Alan T ; Schlecht, Robin W ; Tedjojuwono, Ken K ; Trujillo, Anna C ; Williams, Ralph A ; Kinney, J Bryan ; Barry, John S</td>
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### Safety

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At a subsystem level the research landscape can be described as extremely fragmented. Modern aircraft are extremely complex system-of-systems, and the complexity is expected to increase as the subsystems take on at least some of the tasks of the second pilot, if not all. The impact on each subsystem, and its change in context when moving to SPO, needs to be studied in detail. A lot of the currently available studies, as the literature review reveals, have focused on examining individual systems in isolation. For instance, there are a few studies covered in the literature review that pertain to verbal communications, and crew proximity to each other. Estimating the path forward for SPO needs a subsystem level understanding of costs and complexity, and one of the key factors that make this a difficult task is the amount of software based capability that is present in aircraft these days, for which traditional metrics like reliability are not easily computable. Additionally, the research landscape also includes studies which are not necessarily focused on SPO but whose conclusions are transferrable to SPO scenarios until dedicated studies are done. In the following section of the thesis, some of the key papers dealing with SPO that have been studied will be presented as an annotated bibliography.

In summary, it is evident that research dedicated to the exploration and realization of SPO is in its early stages. NASA through its SPO steering committee is setting high level directions for research, and some of those directions are being explored by academia and other entities in conjunction with NASA. Overall, the literature review for this thesis has been conducted to identify the SPO architectures currently being discussed in research, with a view to comparing them on a trade space of cost versus safety. The concepts identified fall on a spectrum where on one end you have the current two crew scenario, and the other has automation fully taking over from the second pilot. In between, there are various combinations of human and automation teaming to replace the on-board second pilot, with concepts like harbor pilot, ground based UAS pilot, and airborne wingman being mentioned in the literature. As mentioned previously, these are not all discussed in the same level of detail, and the concept section of this thesis will aim to deal with these concepts at a level of abstraction that makes for valid comparisons.
2.1 Annotated Bibliography of Key Papers

2.1.1 Business Case and Viability


This paper by BBN technologies of Cambridge, MA, who are a subsidiary of Raytheon, broadly describes the methodology involved in moving to single pilot procedures. At a high level, it describes the changes required in human performance modeling and single pilot procedure development. The paper uses current models and procedures as a baseline and makes the assumption that automation will take on a lot of the tasks of the first officer, and the captain’s role – and potentially that of the air traffic controller – will be refined. The paper also identifies key technologies that have the potential to become enablers for SPO, and discusses some of the advantages and disadvantages of them. Speech recognition, electronic moving maps, and agent based modeling will play a key role in helping develop SPO procedures, while datalink is identified as having the caveat of added head-down time for the pilot. The paper discusses the role of speech recognition technologies, exploring the possibility of the pilot interfacing with the automation through voice commands as he would with a second pilot. It raises, but does not answer, key questions about the role of voice technology including the implications of a misunderstood command, and the effectiveness of aural warnings and the possibility of unacknowledged alerts.

The paper also discusses a list of accidents illustrating human factors failures in two person operations that directly translate to SPO, or have a significant effect in a different form. These include the roles of biases, acts of omission, missing knowledge, problem solving tunnels, and communication in challenging situations. The paper concludes by suggesting that while the authors have suggested an architecture involving the automation directly replacing the duties of the first officer or PNF, other ideas may be invited from the pilot community, whose buy-in is vital for SPO to be possible.
This paper by Don Harris of Cranfield University in the UK sets out a human-centered approach to the development of single pilot aircraft for commercial operations. The paper traces trends in the origin of flight decks, including improvements in safety and automation as well as reduction in crew numbers, and makes the case that the barrier to SPO is not technology per se, but instead is the combination of technology, user interfaces, and creation of new concepts of operation designed to support a single pilot.

In analyzing the factors pertinent to SPO, the paper posits that certain types of accidents can be reduced by moving to SPO, namely those caused by misunderstandings or miscommunications between the crew. It also suggests — unlike the Raytheon report mentioned previously — that simply moving the tasks of the second pilot to the automation may not perhaps be the best architectural approach. The paper also examines the possibility that pilot workload may actually be reduced in moving to single pilot operations. It envisions the role of the pilot as a strategic operator involved in high level goals of route planning. It suggests that the pilot — who today is a monitor of systems that monitor the automation — may be relieved of his monitoring duties entirely, arguing that there is very little the pilots can do in case of a failure. As an extension of this idea, Harris posits that the aircraft will be designed such that the pilot can fly it manually if he chooses to, but this will be a reversionary mode, with the automation taking primary position.

The paper also defines the pilot as the key link between automation and the operating context. Context is important in identifying operational situations beyond the capabilities of automation. These include “corner cases”, for e.g. a CAT III Autoland system’s inability to detect a runway incursion. The paper also explores issues related to pilot incapacitation, and suggests that while these are rare events, the key challenge is detecting impairment as opposed to fatalities. The paper suggests that driver impairment detecting technologies developed by automobile manufacturers are relatively unobtrusive, and could hold the key to detecting pilot incapacitation. Since this paper is from 2007, it predates the advent of wearable technologies that are popular today. The second challenge in pilot incapacitation is the
recovery of the aircraft, and Harris suggests that a ground based operator may take over in those situations, citing the operational experience with large UAVs in the military.

The paper identifies a few human centered research approaches that in the author's view are key to enabling SPO – the interface between the operator and automation, human factors procedures for the SPO cockpit, human error prediction models, and physiological monitoring. A key omission in the paper is the issue of subtle incapacitation especially when caused by mental health issues, though that issue has gained prominence much later than when the paper was published.


This paper makes the case for a human factors based approach towards SPO by arguing that the greatest challenges in moving to SPO lie in developing user interfaces, integrating technologies, and creating new concepts of operation. The authors describe an architecture that involves a ground based control station and crew. The aircraft system remains similar to what it is today, and it is envisioned that the flight would have a second pilot and real time engineering support based on the ground. The authors also describe a system mirror on the ground which replicates state of the aircraft systems and automation, and will store a last known configuration in case of datalink failure. They then attempt to model this based on four options: single pilot, single pilot with ground mirror, single pilot and ground pilot, and single pilot and ground pilot with ground mirror.

The authors treat the pilots as a part of the wider sociotechnical system that includes players like ATC, ground handling, and fueling. The paper details a cognitive work analysis conducted on current flight operations to identify how the tasks are shared between the players in this sociotechnical system, and how they interact among themselves. They use social network analysis to demonstrate that removing the pilot monitoring from the picture dramatically increases the amount of network interactions on the remaining pilot, which can be interpreted as a concurrent increase in workload. Further modeling on the
concept options suggest that the option where the single pilot is assisted by a ground pilot and a system mirror on the ground appears to be the best in terms of reducing dependencies on the single pilot.

The authors conclude that instead of adding automation to existing aircraft systems to enable SPO, a better approach may be to incorporate a distributed ground/air sociotechnical system that displaces the many of the second pilots functions to the ground instead of replacing them via automation. They also suggest that often the quality of such assistance rendered from the ground may be higher than that available in the air from a second pilot, who may commit the same errors as the other pilot on board.

This publication details the proceedings of NASA’s technical interchange meeting on SPO. It is a collection of expert opinions and workshop results summarized from three days of meetings. The expert opinions start with Dr. Sheridan Thomas of MIT, who outlined the following challenges in moving to SPO:

- Automation failures and levels of appropriate automation in SPO
- Communication issues when a ground based crew member is involved
- Potential Increase in the single pilot’s workload
- Social context of SPO (boredom, down-time)
- Cooperation issues, conflict identification, and conflict management between different agents in SPO
- Communication between the human and automation
- The relationship between Authority, Control and Responsibility, and when to give control to the human operator.

Dr. Amy Pritchett from Georgia Institute of Technology talks about modelling the work of the flight deck. She raises the following key issues:
The role of team members – an increase in team members may lead to a decrease in work performed per team member, but increase the total volume of work performed, due to overheads of co-ordination and redundancy. Increasing team members increases the redundancy in tasks performed, but humans are capable of committing similar errors.

She elaborates on her work in creating models of the flight deck task, especially in approach and landing scenarios. These models are capable of determining the appropriate levels of automation for various scenarios based on different metrics. She also introduces a conceptual model where the process of completing a task is modeled as an agent within an environment – the environment seeks actions from the agent, and the agent seeks information from the environment. In a two crew cockpit, for instance, the second pilot would be treated as part of the environment for the first pilot.

Dr R. John Hansman from MIT’s International Center for Air Transport presented the following ideas:

- Dr. Hansman examines motivations for moving to SPO, including crew and labour costs, historical trends of de-crewing, and safety improvements with the advent of increased automation.
- In addressing the safety issues, he notes the increased reliability and redundancy required from the aircraft systems for them to be certifiable. The system must be “fail safe, fail operational”.
- He also addresses the issue of redundancy in the human components of the system. In this regard, he posits some interesting ideas like training flight attendants as backup crew members, designing easy to use recovery functions (e.g. “Straight and Level” button on Avidyne DFC90) such that civilians with no flight experience may be able to command a recovery, and also the ability of the aircraft to perform an automated recovery.
- He addresses security issues in the architecture, including the need for paying attention to terrorism. If a flight attendant were to be designated back up, the issue of cockpit access must be looked at. If a ground based crew member can control the aircraft, safeguards must be in place to prevent them from harming the aircraft, particularly since they can do so with little harm to themselves.
- Additionally, Dr. Hansman states that the integrity of communications architectures and the ability to deal with non-normal operations will play a key role in realizing SPO.
Captain Robert Koteskey, a professional pilot who works as a researcher for the NASA Ames Flight Deck Display Research Lab as part of the San Jose University Research Foundation, discussed the following points:

- Using a notional risk threshold on a graph plotting the number of events that require pilot action and the difficulty associated with handling the event, Captain Koteskey makes the case that technology and CRM have kept most (but not all) events below the risk threshold. He makes the case that SPO should incorporate lessons from decades of CRM research and operational experience, since CRM today includes not just the interactions between pilots, but also the web of teams and automation that may exist in environments external to the flight deck, like ATC and F/As.

Ms. Leigh-Lu Prasse from ARINC introduced the following two concepts:

- Single pilot backed up by Unmanned Aircraft System capabilities – in this architecture, the single pilot is in an aircraft of capabilities analogous to current UAS technology, in essence making it an optionally piloted aircraft. She indicates that this is the safest and most feasible option to follow. In the event of off-normal situations like loss of communications, the aircraft response may be pre-programmed. She raises (but does not answer) pertinent questions on the role of the ground based pilot, including the number of aircraft they can supervise, the number of hours they can be on duty, as well as how the remote pilot can be handed control by determining when exactly the on-board pilot has been incapacitated.

- The second concept envisages a super dispatcher in the Air Operations Center of an airline, an active member of the loop that also includes the pilot and ATC. This concept sees the super dispatcher take on the role of a remote co-pilot but without the flying capabilities. It stresses on the need for dispatcher-pilot and dispatcher-ATC communications to be certified to the same standards as CPDLC, but does not address the question of off-normal operations or pilot incapacitation. The paper also notes that some airlines have an off-duty captain in a 24 hour role similar to a super dispatcher today, to play the role of an expert who augments the knowledge available in the flight deck.
Dr. R. Michael Norman from The Boeing Company addressed the economic opportunities and technological challenges related to SPO, enumerated as follows:

- Dr. Norman examines various issues related to reduced crew operations, and identifies key technological factors that may help mitigate these issues. In terms of safety of SPO, his analysis of accident data from operators under FAR Part 121 (commercial air transport), Part 135 (unscheduled and commuter), and Part 91 (civilian non-commercial) operations reveal that the current two pilot operations in Part 121 are one to two orders of magnitude safer than Part 135 or 91 operations. Part 135 has some aircraft that are certified for single pilot operations, and part 91 sees a large number of single pilot GA operations. In moving to SPO, the design must maintain or achieve levels of safety better than current levels in Part 121 operations.

- Dr. Norman’s case for economic benefits uses the metric of pilots per seat, aircraft crew size and year, to determine world-fleet-wide costs of each cockpit seat for a 20 year service life (based on Boeing market forecast from 2005-2025) to be $6.8 trillion, which is a significant percentage of the projected fleet acquisition cost of new airplanes estimated at $12.6 trillion. This study does not take into account the increased costs incurred by moving to SPO, and Norman suggests the use of more efficient scheduling and reduced crew augmentation as areas for minimizing pilot numbers. He also suggest that flight decks may be designed solely for SPO.

- In his section on SPO safety, Dr. Norman states that while SPO can be certified under current FAA regulations, the language in some of those regulations may show a reluctance on the part of the FAA. He identifies enabling a single pilot to conduct complex operating procedures (sometimes simultaneously) in normal, abnormal, and emergency scenarios, accommodating actions and procedures requiring a pilot to be unavailable at his/her assigned duty station, avoiding failure of automation in aircraft systems and control, accommodating communications and navigation workload, avoiding increased workload associated with any emergency that may lead to other emergencies, and mitigating the effects of pilot illness or incapacitation as key challenges in the certification of SPO.

- With regards to pilot incapacitation, Dr. Norman uses data from January 1987 to December 2006 to conclude that pilot incapacitation is a serious issue. The rate of 10 events per billion flight
hours as seen in Part 121 operations, which represented the highest levels of safety, would lead to the conclusion that the human operating the aircraft, if treated as a system when it comes to reliability, would not be certifiable since it does not meet the reliability criteria. To mitigate the reliability issue, he suggests that screening for arteriosclerosis and cerebrovascular diseases—which made up the bulk of causes in his study—be used to eliminate the biggest risk factor. He also suggests the use of pilot identification systems (possibly using biometrics) to prevent unlawful operation of the aircraft, including using databases to identify expired certificates.

- He also suggests that an incapacitation detection and aircraft recovery system be designed, where the incapacitation detection rate should have a reliability of 1 incident missed in every billion flight hours. For the recovery ability, the aircraft should be designed such that it can operate autonomously in any stage of flight.

Mr. Steve Boyd from the FAA’s Transport Airplane Directive provides a regulatory perspective on SPO:

- Boyd lists out the minimum flight crew requirements as they are stated in the FARs, and identifies ten key factors that guide the determination of minimum crew. It is significant to note that the FARs do not specify a minimum number, the minimum is determined based on performance. He cautions that special conditions will have to be written to accommodate the certification of new automation features designed to take on the task of the second pilot.

- SPO should be seen in the context of NextGen air traffic management concepts, taking into account increased traffic as well as the proposed transfer of some of the ATC monitoring functions to the pilot. This may exacerbate workload especially in off-normal operations.

- Boyd stresses the importance of pilot incapacitation, and advocates a reversal of current design principles; currently, a pilot can take over when an aircraft system or automation fails, but in the context of SPO, the aircraft must be designed to take over when the pilot “fails”. This, he posits, would require new approaches to aircraft system design.

- In terms of safety requirements, Boyd predicts that hazard categories for many existing systems may be elevated when moving to SPO, requiring more robust design. SPO designs may increase the total number of failures considered significant.

- Boyd also states that safety requirements were mostly written when functionality was in the hardware, whereas modern aircraft systems have a high percentage of their functionality in
software. Failure probability for hardware can be determined, but software failures are often due to design errors and it is difficult to assign probability. Software are classified based on their criticality, and manufacturers often try to move their software to lower criticality classifications to reduce expense when possible. This problem will likely be exacerbated by the move to SPO.

2.1.2 System Architecture and Analysis


This NASA paper – the result of a study to facilitate the expected boom of very light jets in the 2000s – describes a flight deck system design based on the concept of ‘complemation’ (Schutte 1999), wherein the automation and human are structured within the system as independent entities with complementary capabilities. The authors propose a mission director role for the pilot, with the automation in charge of inner loop controls like precisely maneuvering the aircraft, and the human gives high level directions to the automation for every required speed or direction change. In this method, the authors argue, the human is more involved in the process than (s)he would be when merely watching over the automation, and helps update the pilot’s mental model in a manner similar to that achieved by making frequent position reports. The pilot also plays additional roles of troubleshooter and back-up to the automation.

The authors call for the use of artificial intelligence and metaphors in interface design to decrease what they describe as the cognitive distance to perform a task: for e.g., when a pilot receives instructions from ATC, he must first process them to understand what is required of him, and then recall the steps or tasks involved in programming the automation to do the same. The authors contend that reducing this distance decreases mental workload without sacrificing situational awareness. There are four metaphors proposed by the authors:
• The human metaphor – in this instance, the automation takes the conceptual form of a human, and may be relied upon to provide knowledge-based reasoning, information, and behaviour. The automation interacts with the pilot through multimodal means including naturalistic ones like voice recognition and response. The authors suggest this may be used in non time critical tasks.

• The domesticated animal metaphor – in this case, the automation is relied upon for skill based behaviour. The authors use the metaphor of a horse, and suggest that the human in charge can control the behaviour of the automation in a manner conceptually similar to how they would ride a horse. They may be relied upon to navigate all sorts of terrain, and obey the riders commands though a limited means of communication, and can challenge dangerous behaviour on the rider’s part. The authors recommend this metaphor for performing time critical tasks where the pilot need not be aware of the minutiae of the automations state.

• The body metaphor – here, the authors propose that the automation be treated as an extension of the human operator’s body. The automation enhances, empowers and extends the human’s capabilities. This is suggested as a backup for the pilot when his skill based behaviours are required in the performance of a task.

• The tool metaphor – the automation is used in task specific scenarios, similar to a tool.

The paper further describes and investigates the concept of a single pilot aircraft using the animal metaphor primarily, and explores its behavior under a limited set of operational scenarios. The authors conclude that the metaphor allows for a consistent design that can expand to accommodate new technologies. They also stress upon the need for a human centered approach to design, as opposed to a technology centered one which often leaves the pilot as a spectator to the automation. These approaches do not include the unexpected, and often leaves the operator unable to deal with the same. The authors contend that humans complemented by automation can perform better and enable common sense solutions in fuzzy operational scenarios like weather related situations, which cannot be modeled to greater than 90% accuracy.
This study focuses on the feasibility of having a ground based crew member, investigating the question of how much situational awareness such a crew member needs prior to assisting a flight remotely, especially in off-nominal situations. The study defines two concepts of operation—one where the aircraft is handed off from a dispatcher to a specialist for dedicated assistance (who comes in with no prior situation preview, or awareness of the state of the aircraft and its systems) and the second has a hybrid dispatcher who can perform pilot duties as well, who hands off all aircraft under his control to other dispatchers allowing him to focus on the needs of one aircraft (low to high situation preview based on level of interaction with aircraft prior to situation arising).

The subjects rated all tested aspects of the specialist vs. hybrid questions at statistically the same level, with only flight safety being described as being significantly better under the specialist concept. The introduction of an aircraft control list that lets the ground operator keep track of aircraft under his authority was rated positively, though there was confusion in some subjects as to the nature of the handover of other aircraft when a particular aircraft needed dedicated assistance. The tools introduced in the test to aid sharing of situational awareness—traffic situation display, shared charts, and CRM indicators—were rated overall as useful by the subjects. Subjects commented that video feed may not be useful in the context of the experiment, though it may be useful to detect incapacitation.

Overall, the study concludes that the initial level of situation awareness of a ground operator is not really a factor in their ability to provide effective assistance when called in to play the role of an F/O, if the ground station adequately displays information related to the aircraft, its systems and its environment that allows the operator to quickly gain SA. This suggests that either the specialist or the hybrid concept of operations could work in this scenario. The caveat is that this test involved enroute situations, and results might vary in high workload situations like takeoffs and aborted landings. The paper proposes a
‘harbor pilot’ concept where dedicated assistance is available to aircraft in all arrival and departure scenarios.


This paper reports on a series of workshops conducted with crew members from different departments (flight crew, flight attendants, ground handling, flight dispatch, flight operations control, and safety) at five European airlines to determine new sociotechnical models that describe the flight crew task. The paper posits that work task based models derived from airline SOPs often have limitations since they do not reflect real world conditions. For example, checklists in an SOP may be interrupted for different reasons, and may be continued when the cause of interruption is no longer a factor. Similarly, while flight crews value procedures due to their safety benefits, they often deviate from or work around procedures when the complexity of the situation demands it, or when the SOP fails to adequately address a situation. Current models also fail to take into account the nature of teamwork, especially the teamwork that happens outside of the immediate flight crew environment like maintenance and training, and the effect these have on flight crew task performance.

The authors propose a process based model of flight crew tasks that treats the humans in the flight deck as a coordinating interface between various human agents and technical processes that are involved in the successful completion of the flight task. They study the relationships between flight crew performance and key sociotechnical elements in the flight process, flight crew performance and the process levels involved in the flight process, and flight crew performance and duty status. They then combine these to form a process based sociotechnical model of the flight task. Moving to a process based model, the authors conclude, better incorporated the collaborative requirements involved at various process gates. They suggest that this model can be used in designing or improving performance management, the flight operations process, and new tools that support flight crew tasks.
From the point of view of SPO, the detailed flight crew task process model described as a series of process gates and decision points by the workshop participants, can serve as the basis model from which SPO induced changes may be evaluated. As a first step, this model may be expanded to reflect off-nominal processes, and decomposed one level down to include the systems that play a role in each of these flight processes.


This paper starts out by discussing some of the high level concepts and concern covered by the NASA SPO TIM Report, such as communication issues, pilot incapacitation, and certification hurdles. The paper goes on to investigate air-ground teams as an SPO architecture. The paper identifies that the availability of ground based crew members like dispatchers who could take on high-workload strategic tasks like re-routing via ACARS communications was a key factor in the FAA allowing airlines to move to reduced crew operations from three crew members to two crew members.

The paper identifies that the presence of a remote crew member may be advantageous in unexpected situations of high workload that the automation isn’t designed to handle. A human operator may also be useful when there is a failure of automation, which may require human problem solving skills. The ground based team member can also serve as an additional source of knowledge, much the same way dispatchers help plan routes today. A ground based team member could also aid in the detection of incapacitation, and some of the authors of this paper believe that a human should be the one detecting incapacitation in a pilot. A ground based team member can also alleviate boredom on long flights through social interaction, and also provide the social pressure to the on-board single pilot to “stay on the ball” and perform duties diligently.
Air ground teams will face challenges in task division between the airborne and ground based pilots. It will also require an examination of CRM. Also, there needs to be more study to determine how many aircraft a ground based pilot can handle at one time. A one to one ratio seems would suggest cost savings so low that it does not make economic sense to pursue such an architecture.

The paper concludes by suggesting future studies that explore relations between proximity of crew members and their performance, as well as studies further down the road to support the creation of ground based dispatch stations.


This paper describes the results of the study proposed by the previous paper, which was conducted by having 18 crews fly challenging off-nominal scenarios in three configurations: baseline, SPO without collaboration tools, and SPO with collaboration tools. The authors explore the air-ground approach to SPO (as opposed to aircraft/automation centric approaches) using human in the loop studies, with each successive study utilizing a more advanced ground station and more evolved concept of operations. The authors describe two tests that were conducted. In SPO 1, the crew operated a rudimentary aircraft simulator that was split into two identical flight decks, with the crew members unable to see each other. This test reveals that in today’s baseline scenario a lot of actions can be acknowledged non-verbally, and while the acknowledgement can shift to other means, it may require extensive radio communications between crew members at separate locations.

In the second test, the authors introduced a series of tools designed to enable SPO operations. While one crew member was seated in a high-fidelity flight deck, the other was seated in a ground station that
combined information from the aircraft alongside some of the functions of a dispatcher. The tools included shared displays and charts, a video feed designed to allow crew members to see what the other crew member was looking at, CRM displays designed to allow sharing of tasks and duties, and other specialized warnings.

Overall, the paper concludes that while the pilot subjects preferred baseline configuration (because of the fact that they have thousands of hours of experience in that scenario), SPO concepts were generally deemed successful, though not as much as baseline concepts. Other factors causing the relatively poor performance compared to baseline were attributed to issues in the design of the tools and experimental setup.

A few interesting factors to note from the study are that SPO 1 had identical post-trial ratings for pilot situational awareness, but there was significant variation in SPO 2. While shared displays, charts and CRM indicators received generally positive ratings from pilots, they rated the video feed as a distraction, and found it not very useful since they could not tell what the other crew member was looking at. This was because the second crew member was in a station that was designed differently from the flight deck. It was also interesting to note that pilot ratings of the feasibility of SPO went down when comparing ratings before and after the trial.

Overall the paper concludes that separating a two person crew is feasible within the parameters that were tested, and that operations were conducted successfully, though pilot preference ratings indicate that baseline configuration is more preferred.
2.1.3 Safety

This report describes the facts, causes, and recommendations determined by the investigation into the crash of Helios Airways flight 522, a Boeing 737-300 aircraft operating between Larnaca in Cyprus and Prague in the Czech Republic, on 14th August 2005. The Greek AAIASB conclude that the aircraft crashed due to fuel starvation as the aircraft flew with its pilots incapacitated by hypoxia brought on by incorrect actions by the flight crew and maintenance crews which led to the pressurization system being left in manual mode with the outflow valve one third open (preventing pressurization). A cabin altitude warning that sounded as the flight crew climbed through 16,000 feet was misinterpreted as a takeoff configuration warning, and the crew failed to notice the status of the pressurization system on multiple occasions. Fighter jets scrambled to intercept the aircraft after it stopped communicating with ATC noted that passengers were motionless in the cabin with oxygen masks deployed, and that there was someone (believed to be a flight attendant) in the captain’s seat, with the F/O slumped over in his seat. The autopilot had continued flying the aircraft until it entered a hold over the KEA radio beacon, and subsequently crashed when it ran out of fuel.

In addition to the causes and facts described, the AAIASB also identifies as latent causes the deficiencies in the airlines maintenance procedures, the inadequate oversight by regulators over airline maintenance practices, the breakdown of CRM in the operating crew, and the failure of the manufacturer to respond to previously reported incidents of malfunction in the pressurization system. The recommendations primarily cover maintenance procedures and cockpit checklists involving the pressurization system. Clarifications were also issued over the correct identification of the takeoff configuration warning and cabin altitude warning, and correct responses were identified.
This report describes the facts, causes, and recommendations determined by the investigation into the crash of GermanWings flight 9525, an A320 aircraft operating between Barcelona in Spain and Dusseldorf in Germany, on 24th March 2015. The French BEA conclude on the basis of their investigation that the airplane was deliberately brought down by the actions of the first officer, who used the autopilot to fly the airplane into terrain by changing the altitude setting after locking the Captain out of the flight deck when he stepped out to use the restroom. The investigation also determined that the pilot had a history of depression and mental health issues, and had his medical certificate denied revalidation once due to him undergoing treatment for the same. The certificate was later reissued with the caveat that it would become invalid if he relapsed into depression.

The investigation determined that the F/O was undergoing a depression episode with psychotic symptoms, and that he had not sought medical help. The fear of losing his ability to fly, the financial costs of losing his career, and the lack of clarity in German laws to help determine when public safety is greater than patient privacy are all cited as probable causes for the incident. Safety requirements after 9/11 have made flight deck door resistant to outside intrusion, and the design prevented the re-entry of the captain back into the flight deck before the plane impacted terrain.

The BEA in its recommendations calls for clear conditions to be defined for the re-issue of medical certificates after a revalidation denial due to a mental health episode. They also call for EASA to conduct pilot incapacitation studies with an emphasis on (but not limited to) incapacitation due to mental health issues, and also call for airlines to take steps to mitigate the financial impact of pilots losing their license, which may encourage them to self-report conditions. The BEA also call for pan-European laws to enable medical practitioners to report patients when it is determined that they may pose a threat to public safety.
3. VIABILITY OF SINGLE PILOT OPERATIONS IN COMMERCIAL AIR TRANSPORT

This chapter of the thesis will aim to build the case for single pilot operations by analyzing the viability of SPO at a systems level, focusing on trends and challenges in safety as well as business impact. To uncover these factors, it is important to look at needs of the stakeholders involved in airline operations today, and understand who among those would be impacted by the move to SPO, and how. Different groups of stakeholders will see their value move in differing directions as a result of such a move. The stakeholders affected by the move to SPO were identified as the following: Airline Management, Aircraft Manufacturers, Captains, First Officers, Regulators, Pilot Unions, Air Traffic Control, Academia, Dispatch, Trainee Pilots, Flight Attendants, Ground Staff, and Passengers. Captains, First Officers, and Pilot Unions were treated separately since they are affected differently despite being similar groups in function with significant common interests.

The Figure 7 maps the power versus influence of various stakeholders affected by SPO. The key players, identified in the upper right quadrant, are airline management, aircraft manufacturers, and pilots. Any solutions eventually identified will also need to address the needs of the groups in the upper left quadrant, namely regulators (FAA, EASA etc.), pilot unions, and air traffic control. Those in the lower left quadrant have very little interest and influence in moving to SPO, but it should be noted here that passengers can move up the power and interest axes if galvanized by perceptions and opinions about factors like safety. Amongst those in the lower right quadrant, academia and institutions like NASA will play key roles as drivers and enablers who put in place the research, safety, and technological frameworks in place for SPO to happen.
As can be seen in Figure 8 below, when the interactions of influence between the stakeholders are mapped on the power-interest chart, we can see hubs of influence form around management, manufacturers, pilots (both Captains and F/Os), and regulators. Business interactions converge around management, safety interactions diverge out from regulators, design interactions converge at airframers (and, subsequently flow down to and back from subsystem manufacturers), and operational interactions converge around pilots. At a system level, these are the key stakeholders whose needs this thesis will attempt to address. Academia (and institutions like NASA), maintenance, as well as ATC play
important roles in supporting operations, and while they have a relatively significant amount of power and interest, they will not be studied in detail for the purposes of this thesis.
<table>
<thead>
<tr>
<th>Stakeholder</th>
<th>Type</th>
<th>Power</th>
<th>Interest</th>
<th>Positive Impact</th>
<th>Negative Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Management</td>
<td>Internal</td>
<td>High - go/no-go decision maker</td>
<td>High</td>
<td>Labour cost reduction, Simpler scheduling.</td>
<td>Higher fleet acquisition costs, higher safety overheads</td>
</tr>
<tr>
<td>Aircraft Manufacturer</td>
<td>Internal</td>
<td>High - go/no-go decision maker</td>
<td>High</td>
<td>Increased sales based on lower operating costs</td>
<td>Increased certification costs, design complexity</td>
</tr>
<tr>
<td>Subsystem Manufacturer</td>
<td>External</td>
<td>Medium - technology enabler</td>
<td>High</td>
<td>New business creating SPO-rated subsystems</td>
<td>Increased system complexity, certification burden shared</td>
</tr>
<tr>
<td>Captains</td>
<td>Internal</td>
<td>Medium - most likely candidates to start SPO</td>
<td>Medium</td>
<td>Increased responsibility and compensation, possibly simplified seniority rules</td>
<td>Potentially higher workload, potentially earlier retirement age</td>
</tr>
<tr>
<td>First Officers</td>
<td>Internal</td>
<td>Medium - high career uncertainties due to SPO</td>
<td>Medium</td>
<td></td>
<td>Position may disappear, Harder path to promotion</td>
</tr>
<tr>
<td>Regulators</td>
<td>External</td>
<td>High - go/no-go sanction</td>
<td>Medium</td>
<td></td>
<td>Increased certification burden, Increased safety regulation</td>
</tr>
<tr>
<td>Maintenance</td>
<td>Internal</td>
<td>Medium - maintainability key concern in new aircraft types</td>
<td>Low</td>
<td>Possible simplification of some maintenance and inventory</td>
<td>Possible new safety regimes (similar to ETOPS) for SPO may increase burden</td>
</tr>
<tr>
<td>ATC</td>
<td>External</td>
<td>Medium</td>
<td>Low</td>
<td>Possible decrease in voice communication</td>
<td>Possible increase in pilot assistance</td>
</tr>
<tr>
<td>Pilot Unions</td>
<td>External</td>
<td>Medium - collective interests of flight crews</td>
<td>High</td>
<td>Possibly simplified seniority rules and scope/contract negotiations</td>
<td>Possible reduction in numbers and leverage over management</td>
</tr>
<tr>
<td>Academia</td>
<td>Beneficiary</td>
<td>Low - enablers, working primarily with manufacturers and regulators</td>
<td>High</td>
<td>Increased research opportunities</td>
<td></td>
</tr>
</tbody>
</table>
Further analysis of the stakeholders and the positive and negative impacts on them are summarized in Table 2 above. Stakeholders are classified as Internal, External, Neutral and Beneficiaries. Internal stakeholders are defined as those stakeholders who are directly affected by the move to SPO - i.e., the nature of their role under today’s operational concept is significantly altered. Indirect stakeholders are those stakeholders who have a say in the overall concept of operations, but are not directly affected by the move to SPO. Neutral stakeholders are those who neither wield power nor have interest in the effects of SPO. Under some possible concepts of operation, these neutral stakeholders may face minor additional duties which are not deemed significant in terms of their overall impact on SPO. For example, gate staff may be required to help with additional screening for mental health of pilots, but this cannot be considered as something that directly affects core architecture. The only beneficiary stakeholder is academia, which faces no significant negative impact, and stands to receive funding for research projects required to develop and sustain SPO.
A shortcoming of this analysis at this point is that the stakeholders are very clearly identified based on two-pilot operations in existence today. As such, entire classes of stakeholders may emerge once architectures are developed. An obvious example would be a ground based co-pilot who assists the single pilot with some duties in certain phases of flight. This is not a class of stakeholder that exists today, but could emerge as a significant internal stakeholder under architectures calling for a ground station, and will have interests, influence and impact different from that of a first officer today.

From the perspective of management, it can be seen from the stakeholder analysis that the case for SPO should be built by exploring whether the marginal cost increases in fleet acquisition and safety overheads incurred by the move to SPO are outweighed by the reduction in labour related costs. For the manufacturer, it can be argued that the move to SPO may be no more complex than other epoch-changes in the past, like the move to jet engines, glass cockpits, or ETOPS. Pilots as stakeholders face significant challenges in moving to SPO. In addition to the challenge of merging the functions performed today by two pilots into something that can be handled by one without increasing the workload or compromising situational awareness, the pilot as a system operating the airplane needs to be scrutinized because (s)he now becomes a single point of failure. Effectively, the viability of SPO at a high level boils down to the answer to the following two questions:

- *Can commercial air transport operations be conducted with a single pilot operating the aircraft?*
- *Is it desirable to operate commercial transport aircraft with only a single pilot?*

### 3.1 Can commercial air transport operations be conducted with a single pilot operating the aircraft?

Essentially, this is a question that boils down to safety, redundancy and reliability. Currently, the two pilots in charge of operating the airplane are an extension of the concept of redundancy that is found in practically every other subsystem on board the aircraft. Just as there are three hydraulic systems, four
flight control computers, or two air-conditioning packs— all in place to ensure safe operations in case one system fails— there are two pilots who, unlike the other systems mentioned, divide tasks between themselves instead of duplicating it. This division of tasks and collaboration between them in completing said tasks is designed to ensure the safe operation of the flight, in a manner that will not overwhelm the capabilities of any one crewmember. And like the aforementioned systems, in case a pilot becomes incapacitated, there is a remaining crew member who can bring the aircraft to a safe landing. Reducing the number of crew to one also open up the question of division of tasks— it may not be possible or feasible for a one-to-one replacement of the second human with automation capabilities, and some residual tasks may move to the remaining pilot, depending on the characteristics of the architecture chosen. The viability of single pilot commercial operations from a safety standpoint requires the identification of safety issues that may uniquely affect single pilot operations, and possible solutions for the same. Hence, the two key issues to be looked at in this section are the question of pilot workload, and that of pilot incapacitation.

3.1.1 Pilot Workload – An Overview

A key concern that repeatedly features in the proceedings of the NASA SPO TIM (W. W. Johnson et al. 2013) is that the workload on the remaining pilot may go up when you reduce crew numbers from two to one. Harris et. al, (Stanton, Harris, and Starr 2015) also establish via social network analysis that the number of interactions dependent on the remaining pilot dramatically increases when the second pilot is removed from the picture. It is suggested in both these pieces of literature that the on-board automation may take on some or all of the tasks of the second pilot, depending on the actual architectural configuration. While it is easy to assume an ‘electric horse’ approach of replacing the second pilot one for one with aviation, in reality this may pose many challenges, both obvious and unexpected (Schutte et al. 2007). For instance, the social interaction aspect that prevents boredom and keeps the crew alert on long cruise segments is something that will need to be addressed. Additionally, the idea that automation can fully replace the second pilot also assumes that the technology behind the automation would advance to a level sufficient for it to supplant the tasks currently performed by a
human being. It must then be assumed likely that a real world architecture for SPO may fall somewhere in the midst of a spectrum that extends from fully human to fully autonomous, in terms of who or what replaces the second pilot.

In this regard, the pilot workload may change in two directions. One, as stated already, the responsibility to manage additional systems can place a burden on the pilot above what is currently seen as safe in today’s operation. This may be exacerbated by off-nominal situations, especially ones where the automation itself fails, leaving the pilot with too much on his plate, so to speak (Deutsch and Pew 2005). Extended periods of playing a manger of systems role may also degrade his ability to deal with controlling the aircraft when faced with some of these off-nominal conditions (Schutte et al. 2007). The second possibility is that some of the workload the pilot faces today may decrease, or go away entirely (Stanton, Harris, and Starr 2015). An obvious candidate for this is the workload incurred in cross checking the second pilot’s actions, especially if we assume that the automation would provide more consistency in performance on an aircraft type when compared to flying with different human F/Os every day.

There is a lot of literature covering the level of workload experienced by flight crews under different conditions, and at different stages in flight. There are also established methods for the subjective and objective measurement of pilot workload, as well as studies that measure workload using combined methods (Wilson 2002). Wilson states that the highest variation in psychophysiological indicators of workload happen during the takeoff and landing stages. While there are studies covering off nominal situations, the literature does not present consistent comparisons of off nominal workload measured on a single or - even comparable - metric and any analysis of workload undertaken will need to score workload on a notional basis with weights derived from expert judgement.

To better understand the role of pilot workload, a baseline model of the flight operations process as it exists today must be defined. In terms of workload, the model shall look at the processes being monitored by the pilots in any given phase of flight. From airline SOPs that define the roles of the pilot flying and pilot monitoring, it is possible to create a picture of what processes are under whose responsibility, and then identify where this responsibility shifts (i.e., to automation or a remote crew
member) when the pilot monitoring is removed. Summing the processes now under the single pilot would point to a picture of his total workload. Such a model is described in detail in chapter 4.

There have been numerous accidents in flight operations due to pilot incapacitation. The next section will look at a couple of case studies to try and derive lessons from an SPO perspective.

### 3.1.1.1 Accident Case Studies

#### 3.1.1.1.1 Qantas 32

The Qantas A380 operating flight 32 (ATSB 2010) suffered an uncontained engine failure in flight that was successfully managed by the crew. One aspect of this incident that should be noted is the fact that there were four highly experienced crew members, including two check captains, present on board the aircraft. The captain in command had 35 years of flying experience, and was aided by the other three flight crew members in managing the emergency. The F/O and one of the check captains calculated runway length requirements for an overweight landing while the captain and remaining check captain flew the plane and managed ECAM actions and checklists.

It should be noted that the presence of so many pilots on board was merely a happenstance. A check captain – monitoring the standard flight crew – was being trained by a supervising check captain that day. As a result, the captain in command of the aircraft had far more resources at his disposal than a normal operating day would allow him, and this enabled him to manage the huge workload placed on him and his F/O by an exceptional situation. While such a crew scenario cannot be practical for everyday operations, the key takeaway for SPO is that the quality of support available to the captain of QF32 - especially in terms of an expanded knowledge base and strategic decision support – can be made available to single pilots through dedicated specialists on the ground serving multiple aircraft in a cost effective manner.
3.1.1.2 Asiana 214

Asiana 214, operated by a Boeing 777-200ER with a flight crew of four members on board, crashed short of the runway on descent to San Francisco International Airport (NTSB 2014). In a scenario similar to the Qantas flight described earlier, there were four pilots on board – three captains and a first officer. The captain flying the aircraft was new to the type, and was being instructed by a check captain monitoring him from the right seat.

In this incident, a comparable level of experience on the flight deck produced a dramatically different result from that of the Qantas flight. Admittedly the two crews were in different phases of flight, but the primary cause of crash of Asiana 214 was the mismanagement of the approach. All four crew members failed to monitor the airspeed which was dropping, or recognize why.

With regard to SPO, the key aspect to be noted here is that four experienced pilots were unaware of a combination of modes in the autoflight system that rendered automatic speed control inoperative. In moving to SPO, an increase in the amount of automation is anticipated, and it should encompass a drastic improvement in autoflight mode annunciation and recognition. There are numerous autoflight modes with different capabilities in autopilots today, and the Asiana incident is a reminder that even experienced pilots may be caught unawares by the idiosyncrasies of these. The fact that Asiana 214 was not in a high workload situation prior to the error that caused the crash only serves to underscore this point.

3.1.1.2 Potential Solutions to Manage Workload

While the issue of workload is identified in the literature as a key concern, there are also solutions suggested. As can be seen from the discussion in this section thus far, the solutions fall broadly under two categories – Automation Assistance, and Human Assistance. Both these forms of workload alleviation are explored in the concepts section, in Chapter 5.
3.1.1.2.1 Automation Assistance

Automation assistance could involve a human-automation team that replaces the human-human-automation team in flight decks today. Such a move would need to strike a balance between the workload placed on the remaining human, and his ability to manage or monitor the responsibilities taken on by automation. The literature mentions multiple means of achieving this, including the use of artificial intelligence, user interface metaphors, and advanced multimodal interaction technologies.

3.1.1.2.2 Human Assistance

The second possibility would be to move from the current human-human-automation model to a human-automation—human(s) model, with remotely situated human operators assisting the on-board pilot. Their roles, based on notions gathered from the literature review, can vary from merely being an automation monitor, to strategic decision support, and finally active flight control participation.

3.1.2 Pilot Incapacitation – An overview

In aviation medicine, the “1 percent rule” is often applied in determining the risk of medical incapacitation in a pilot. This rule sets the risk threshold at 1% for medical conditions like heart disease and strokes for a pilot in a given year, and pilots are often denied medical clearance to fly if they do not meet this threshold. Incapacitation of a pilot presents a serious breach of safety even in present day operations where more than one crew member is present. While there are a few studies on the rates and causes of pilot incapacitation, there is very little information looking at the effects of incapacitation in a single pilot operation scenario. In single pilot operations, pilot incapacitation can be broken down into two challenges (Harris 2007): the first is detecting the incapacitation, and the second is the recovery of the aircraft once an incapacitation event occurs.
Table 3 Causes of in-flight pilot incapacitation among UK Class 1 medical certificate holders, 2004 (Evans and Radcliffe 2012)

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

The scope for interpretation of the word 'incapacitation' as well as the current modes of detecting and preventing incapacitation will need to be broadened in a single pilot scenario. This is especially because the role played by the second, functional crew member in detecting incapacitation in their crewmate will have to be performed by automation or other human players. This is particularly exacerbated by the subtler forms of incapacitation, including those caused by mental health issues. Current focus on mental health issues in the industry rely on detection in medical screenings on the ground, and lacks succinct guidelines to deal with an in-flight issue caused by the mental health of a pilot. Additionally, rules issued after GermanWings 9525 crash stipulating that two persons be in a cockpit at all times are a symptomatic fix that does not address systemic causes.

Another issue that needs to be investigated is the influence of alcohol and drugs. Random drug and alcohol tests are mandated by many aviation regulatory bodies. Alcohol violations are recorded when a crewmember has a BAC of ≥ 0.04%, or refuses to submit to a test. Typically, such violations are detected by ground staff, flight attendants, and fellow crew members. While alcohol violations were only linked to 0.13% of commercial aviation accidents with about 440 reported violations (1995-2002), this number
could conceivably increase in a single pilot scenario. An FAA study (R. D. Johnson 2008) using toxicology data from 2000-2007 determined that 9% of pilots involved in fatal general aviation accidents had been flying under the influence of alcohol and illicit drugs. While there are many differences in the standards and procedures between general aviation and commercial air transport, it is worth noting that single pilot operations are highly prevalent in general aviation.

According to a study by the Civil Aviation Authority of the United Kingdom (Evans and Radcliffe 2012) using data reported in 2004, 4.3% of UK pilots with a valid UK/JAR class 1 medical certificate underwent episodes where they were at least temporarily unable to operate an aircraft. 18% of these incidents were caused by musculoskeletal disorders, and 14% by cardiovascular illnesses. Mental health issues accounted for 10% of the reported incidents. The distribution of medically induced incapacitation skewed towards older age groups, with 51% of the incidents reported by pilots in the 50-69 year age bracket.

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

While comprehensive data on global rates of pilot incapacitation is hard to find – and it can certainly be assumed that varying standards and cultural factors will skew the rates differently in different parts of the world - it can be seen from the UK study that pilot incapacitation is a serious issue that needs to be addressed as a key challenge in moving to SPO. Norman (2007) worked out incapacitation rates using data in the US from January 1987 to December 2006 to determine that Part 121 air transport operations had an incapacitation rate of 10 events for every billion hours flown. In SPO, where the pilot as a system has no redundancy, this would cause the reliability rate to fall below the required level of less than one event per billion hours flown.
The NASA SPO Technical Interchange Meeting (W. W. Johnson et al. 2013) also recorded multiple concerns from participants related to incapacitation of flight crew. Some of the ideas discussed for further study in that meeting were automated recovery systems, monitoring and detection of subtle incapacitation, and ground based screening for high probability diseases.

3.1.2.1 Accident Case Studies

3.1.2.1.1 Helios Airways 522
Helios Airways 522 – discussed in detail in the literature review section – is a noteworthy accident when studying pilot incapacitation. The two man crew failed to notice an incorrect setting of the pressurization system, and took off with the outflow valve partly open. This led to a gradual decrease in the pressure inside the aircraft, and the crew eventually were overcome by the effects of hypoxia. The plane continued to fly on autopilot until fuel starvation caused it to crash.

It is important to note that even with two crew members, errors of omission and misidentification of aural warnings occurred, which were identified as contributing factors to the accident. Human error modeling studies may be required to predict how a single pilot would behave in such a situation. The cabin altitude warning which was misinterpreted as a takeoff configuration warning poses another challenge – with an increase in automation, there may well be more such warnings and greater chances of confusion.

While this accident happened on an earlier generation aircraft (B737-300), and accounting for the fact that current generation aircraft do a better job of managing systems like pressurization, it should still be noted that in a single pilot scenario there will be challenges with prioritizing systems information and presenting them to the pilot, as well as with letting the automation make decisions in the background. An SPO aircraft should not only be able to correct itself (or effectively induce the pilot to take corrective action) when taking off in a configuration similar to Helios 522, it should also be able to provide further lines of defense such as physiological monitoring and recovery capability.
3.1.2.1.2 GermanWings 9525

The GermanWings accident – facts of which are discussed in the literature review section – is an interesting case study in the context of SPO. Under the broader definition of incapacitation mentioned earlier in this section, this incident can be categorized as a case of subtle pilot incapacitation that went undetected. The NASA SPO TIM report (W. W. Johnson et al. 2013) mentions the case of a JetBlue pilot who had a mental breakdown in flight and was locked out of the cockpit and tackled by the passengers. Most of the participants in that NASA meeting brought up pilot incapacitation as one of the key factors to be addressed when moving to SPO. The meeting predates the GermanWings accident, and hence the discussion centered on the JetBlue incident, which had a safe outcome due to the second crew member and passengers on board restraining the incapacitated crew member. In contrast, on the GermanWings flight, the F/O deliberately locked out the Captain, who was the person with the greatest chance of detecting and stopping the F/Os psychotic depressive episode.

In the context of SPO, the GermanWings accident raises a lot of troubling questions that need to be answered. First and most obvious is the question of how to detect incapacitation. Experts at the NASA meeting were divided on whether a human should have the final say, or whether automation should be trusted to make this decision. Even if this question were answered, there is no clear consensus on what needs to be done next. Should the pilot then be cut out of the loop, and the plane be sent into auto-recovery mode? Should some of the on-board non-flight crew intervene? If a ground based pilot is in the picture, the question of how much authority can be handed to a person who has “no skin in the game” needs to be addressed. Full authority given to a ground based pilot would also need carefully designed procedures, which prevent him or her from committing the same acts as the GermanWings F/O did. It also opens up questions about security and terrorism.

3.1.2.2 Potential Solutions to Negate the Effects of Pilot Incapacitation

In SPO, pilot incapacitation becomes more challenging to detect, and can be disastrous in any phase of flight including on the ground. Given that incapacitation needs to be interpreted in a broader sense,
potential solutions to overcome pilot incapacitation can be classified under the following categories: Pre-flight, In-flight and Other.

3.1.2.2.1 Pre-Flight

- Influence of alcohol and drugs: current random testing for alcohol and drugs serves primarily as a deterrent against violations. One of the conclusions of an NTSB study (National Transportation Safety Board 2014) was that lowering the annual testing rate from 25% to 10% was associated with a significant increase in the amount of violations, hence it is conceivable that higher testing rates would lead to higher rates of deterrence. A cost benefit study may be conducted to determine the ideal testing frequency up to and including mandatory testing prior to a duty period.

- Role of ground staff: training may be imparted to gate agents or flight dispatchers – people who directly interact with the pilot immediately prior to flight – to enable them to better detect signs of aberrant behaviour, like issue with mental health, and reporting for duty under the influence. Outside of random testing, a non-scientific scan of news reports dealing with pilots under the influence indicates that ground staff and flight attendants often play key roles in identifying issues with the flight crew.

- Mental health screening: In the aftermath of GermanWings 9525, psychometric testing has been introduced as part of the hiring process at various airlines around the world (Sunny Sen 2015). Studies may be conducted to determine the ideal frequency of screening. A toolkit may also be developed for aviation medicine professionals to enable them to identify symptoms more effectively. Regulatory changes may be required in many countries with strict patient privacy laws. A balance will need to be struck between patient privacy and protecting the patient from illegal, retaliatory, or otherwise undesirable actions using their medical history against them.

- Screening for arteriosclerosis and cerebrovascular diseases: since these diseases form the bulk of physical health issues that led to incapacitation events, it may be useful to screen pilots more regularly for symptoms of these diseases (W. W. Johnson et al. 2013). Further study may be
conducted to see if there are regional variations in the specific causes behind incapacitation events due to cultural and lifestyle differences.

3.1.2.2.2 In-Flight

- **Real-time health monitoring**: with the advent of wearable devices with increasingly complex capabilities, as well as widespread availability of internet connectivity in-flight, it may be feasible to have real-time monitoring of a pilot’s vital statistics. According to a 2004 study (Axisa et al. 2004), a non-invasive smart-glove device can detect physical and emotional states of the wearer – further study may be conducted to improve the reliability of such systems, and their accuracy especially in detecting emotions.

- **Ground support**: currently, the availability of a second pilot is instrumental in the successful completion of a flight in case of pilot incapacitation. The second pilot may be replaced by a ‘pilot’ on the ground, who can assist by taking over control of the flight when the on-board pilot is incapacitated. Real-time health monitoring, when introduced into this scenario, may possibly help deal with sudden incapacitation where an orderly handover of duties was not possible. While there are multiple studies dealing with the design of a ground station for SPO, specific studies may be required to identify what role a ground based pilot can play in helping detect subtle forms of incapacitation. The use of video could also play a role in detecting pilot incapacitation: ground based crews watching the pilot on video combined with data on the aircraft’s systems could be an effective solution to cope with pilot incapacitation, and this would leave the final decision on incapacitation with a human.

- **Override**: the ability or inability of pilots to override systems is an area of discussion today, with different manufacturers pursuing different philosophies in this regard. In future SPO scenarios, the question of overriding the on-board pilot will need to be studied further. It may be feasible to allow a ground based operator, or the on-board automation itself, to take over from the pilot under certain conditions. Algorithms will need to be developed to identify erratic behaviour on the part of the pilot alone, separating it from system errors or consequences of unreliable information shared by the pilot and the automation.
• Flight Envelope Protection: in Airbus aircraft today, under normal flight law, there are protections built in place that prevent the pilot from exceeding certain parameters like bank angle and angle of attack (Airbus, n.d.), which protect the airplane from entering certain upset conditions like stall. With the advent of high fidelity databases for worldwide terrain information as well as precision flight capabilities like RNP, and combined with other technologies including pilot health monitoring, it may be possible to expand the concept of flight envelope protection to include more deliberate and non-deliberate pilot actions that may put the aircraft in jeopardy.

• Automated recovery: in SPO architectures that preclude the role of a ground based ‘pilot’, the aircraft may be designed with an automated recovery function. There are multiple design approaches possible for this, ranging from automated detection of incapacitation by the aircraft and subsequent diversion to the nearest suitable field, to a “digital parachute” design where even relatively lower skilled crew members like F/As or civilian passengers on board may give a simple command to the aircraft to recover to a suitable location. Some such research is already happening, and the Avidyne DFC90 autopilot’s “straight and level” button (Avidyne 2012) for automated upset recovery can be considered a rudimentary version of what a digital parachute might eventually look like. (W. W. Johnson et al. 2013)

• Human interaction: some forms of subtler incapacitation, like the effects of a stroke, are often detected only when the affected crew member interacts with other humans. Some pilots today are trained to detect such effects in their fellow crew member. With the second crew member going away in SPO, procedures may need to be designed in a way that encourages human interaction between the pilot on board and other humans in the system, like ground based pilots, ATCs, super dispatchers, or F/As.

3.1.2.2.3 Other Measures

• Stigma and self-reporting (FLIGHT INTERNATIONAL 2016)– in many cultures of the world, there is a stigma around openly discussing mental health issues. In aviation, which has a high number of male, type A personalities, there is often a notion that mental health issues like depression are a sign of weak-mindedness. This often discourages crewmembers from discussing it openly even with medical professionals. In addition to the stigma, there are other incentives to keep mental
health issues hidden – fear of losing employment is one of these. Commercial aviation will require a cultural shift to address the issue of mental health, and frameworks will have to be developed that encourage self-reporting and seeking of treatment, instead of hiding and fear.

3.2 Is it desirable to operate commercial transport aircraft with only a single pilot?

This question constitutes the financial aspect of the problem. Are there any rewards for an airline to move towards single pilot operations? Finding the answers to this question would involve identification of incentives and risks. Pilots constitute the third largest labour group within US airlines’ workforce, and command average wages almost double that of the average employee wage in US airlines. While the average pilot wages (both pilot wages as well as total average wages) vary in correlation with industry cycles and other events like an airline entering bankruptcy protection, they continue to remain a high percentage of the total wage bill, as high as 31% in 2015 (Airlines For America 2015). Additionally, low entry level wages and high entry barriers have made flying a less desirable job, threatening to create a pilot shortage in the coming years which would also incentivize airlines to move towards a smaller pilot workforces. The risk for airlines in embracing SPO lies in the possibility that fleet acquisition costs may increase due to the higher reliability required from aircraft systems to support SPO, and potentially negative public opinion on safety of SPO.

When talking about SPO from a business perspective as opposed to a purely technical one, it is important to take into account context of operation, as well as a few real-world operating constraints. As we examine the business case for SPO in this section, we will take into consideration the division between widebody (twin-aisle) and narrowbody aircraft. Since data was not available for airlines operating a fleet consisting entirely of regional aircraft (like the Embraer E-Jets, or Bombardier CRJs), the analysis will be limited to all widebody types on the one hand, and large narrowbodies (A320 class aircraft) on the other. For purposes of the study, we will look at Southwest Airlines, and Emirates Airlines. Southwest Airlines operates an all-narrowbody fleet comprising of Boeing 737 variants, and Emirates operates an all-
widebody fleet of Airbus A380s, Boeing 777 variants, and A330s. The homogeneity in aircraft types and availability of operational data (MIT Airline Data Project for Southwest, Emirates Group Annual Report for Emirates) will simplify the analysis of the business case. Data from 2014 will be used in both cases. Additionally, Southwest (by virtue of being an LCC) and Emirates are carriers known to place high emphasis on employee productivity, often making the best utilization of flight duty time limitations. This would enable us to determine a savings figure closer to the possible maximum.

3.2.1 Identifying Cost Savings

In this section, the primary objective will be to identify how much money an airline can save by moving to single pilot operations. The process will vary slightly for narrowbodies and widebodies. The process for widebodies will involve identifying average crew costs, numbers of crew (including augmented crews) per flight, fraction of total flights with augmented crews, and expected reduction of crew numbers. Flights with augmented crews can be identified by approximating the number of flights beyond a requisite stage length where FDTLs require augmentation. In narrowbodies, since augmented crews are not required due to the maximum stage length dictated by aircraft range being lower than FDTL time, the fraction of flights with augmented crews will not be a factor. However, FDTLs in the US can vary between 9 to 14 hours (FAA 2011) depending on the start time of the pilot. Total flight time can vary between 8-9 hours depending on start time. This has been mandated by the FAA to take into account fatigue experienced by pilots who fly through their window of Circadian-low. Since it is difficult to determine the exact reporting times of pilots due to lack of such publically available data, the analysis will attempt to determine a maximum and minimum possible crew reduction value using the FDTL limits of 9 and 14. In both cases, multiplying the expected crew reduction by average compensation will indicate possible labour savings.

3.2.1.1 Southwest Airlines

Southwest Airlines (IATA code WN) is an LCC based in Dallas, TX. They operate a large homogenous narrowbody fleet comprising of variants of the Boeing 737 aircraft. They have pilot bases at Atlanta,
Baltimore, Chicago, Dallas, Houston, Las Vegas, Oakland, Orlando and Phoenix, and Chicago-Midway is their busiest airport with up to 265 daily departures in peak season (Southwest Airlines 2016). WN is also the largest LCC in the US, both in terms of fleet size as well as revenue. Using data available publicly on the WN website as well as MIT's Airline Data Project website, the following key metrics have been identified as shown in Table 5.

Table 5 WN Key Metrics (Southwest Airlines 2016; MIT Airline Data Project 2014)

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
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<tbody>
<tr>
<td>Fleet Size</td>
<td>623</td>
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<tr>
<td>Number of Pilots</td>
<td>7,497</td>
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<tr>
<td>Average Pilot Compensation</td>
<td>$197,782</td>
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<tr>
<td>Pilot to aircraft ratio</td>
<td>12.034</td>
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<tr>
<td>Average Pilot Block Hours / Month</td>
<td>55.6</td>
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<tr>
<td>Departures per day*</td>
<td>~3400</td>
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<tr>
<td>Departure per day / aircraft</td>
<td>5.53</td>
</tr>
<tr>
<td>Average fleet utilization hours / day</td>
<td>11.01</td>
</tr>
<tr>
<td>Average Stage Time hours</td>
<td>1.99</td>
</tr>
</tbody>
</table>

* - Daily departures face seasonal variations

Average stage time in hours, calculated by dividing average flight utilization per day per aircraft (11.01 hours) by the average departures per day per aircraft (5.53), is determined to be 1.99 hours. Assuming all pilots are on a 9 hour FDTL, it can be reasonably extrapolated that each crew pair can operate three average stages per day, with the remaining ~3 hours being spent in turnarounds on the ground. Dividing the daily number of departures (3400) by three, we can determine that 1133 crew pairs, or 2266 pilots are required to operate an average day's total flights. In reality this number will be much higher due to constraints imposed by crew positioning and domicile. It should also be noted that the total number of pilots, 7497, also includes or accommodates pilots on rest period during a given day, management pilots, pilots under training, pilots on holiday/leave, and pilots on furlough. It is also noteworthy that there are
typically more F/Os than captains. Assuming a conservative 5% reserve of 113 pilots, it can be assumed that at least 2379 pilots are on duty on an average day.

By moving to SPO, this figure can be reduced by 50%, since WN does not need crew augmentation as their longest sector (Baltimore-Oakland) is well within FDTL limitations. This means that 1190 pilots are required for a typical WN duty day under SPO, meaning 1190 are eliminated. Southwest incurs a cockpit cost of $807 per block hour (MIT Airline Data Project 2014). Assuming a conservative 65-35 split between Captain and F/O costs, the airline spends $282.45 per block hour on the F/O. In a given duty day, this works out to $1694.7 taking into account the earlier assumption of 3 daily sectors two hours long on average. For 1190 first officer positions eliminated, the daily savings works out to $2,016,693, leading to an annual savings of $736 million. Using the same methodology, assuming all pilots are at 14 hour FDTLs operating five daily average sectors, the savings work out to $365 million annually. Hence, it can be assumed that Southwest Airlines can save in the range of 365-736 million dollars, with the real figure being contingent on the number of block hours the average pilot flies in a day.

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
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<tbody>
<tr>
<td>Total Revenue 2014</td>
<td>$18.61 bn</td>
</tr>
<tr>
<td>Total Expenditure 2014</td>
<td>$16.38 bn</td>
</tr>
<tr>
<td>Labour Related Expenditure 2014</td>
<td>$5.71bn</td>
</tr>
<tr>
<td>Lower estimate of annual SPO savings</td>
<td>$365 m</td>
</tr>
<tr>
<td>Savings as a % of total expenditure</td>
<td>2.22%</td>
</tr>
<tr>
<td>Savings as a % of labour expenditure</td>
<td>6.39%</td>
</tr>
<tr>
<td>Higher estimate of annual SPO savings</td>
<td>$736 m</td>
</tr>
<tr>
<td>Savings as a % of total expenditure</td>
<td>4.49%</td>
</tr>
<tr>
<td>Savings as a % of labour expenditure</td>
<td>12.89%</td>
</tr>
</tbody>
</table>
It must be noted that this analysis lacks the data to accurately determine actual savings, since only average salaries are publicly reported. The real world constraints imposed by seniority and FDTL actuals are not taken into account in determining the savings. In reality, regardless of the actual figure, some fraction of these savings will go towards fleet and infrastructure costs, and possibly towards new staff types, especially if the architecture calls for ground based pilots. However, these are expected to be cumulatively much lower than the savings created due to SPO. For example, using 2016 list prices of A320 ($98.0m) and A320neo ($107.3m) - chosen because they represent a generational change in aircraft, and it may be reasonable to assume a similar pricing difference when moving from current to SPO generation aircraft - and assuming a conservative discount of 40% with the differential spread over a 20 year aircraft life, a fleet of WN’s size with 623 aircraft would incur an additional cost of $173 million annually for the total fleet. Further study is also needed reveal the requisite number of ground based pilots for a given network (assuming they can monitor multiple flights), recommended compensation scales, and total expense incurred.

3.2.1.2 Emirates:

Emirates (IATA code EK) is an international airline based in Dubai, UAE. They operate a fleet consisting exclusively of widebody aircraft, mainly the Airbus A380 and Boeing 777 alongside a handful of A330s and A340s. Emirates flies long international routes from their hub in Dubai, and their average stage length for the fleet is approximately 2700 nautical miles. This is almost 650 nautical miles more than Southwest’s longest route operated. The longest flight operated by Emirates today is the longest commercial flight in the world, Dubai to Auckland on a Boeing 777-200LR. In operating such long routes, the concept of flight duty time limitations and augmented crews come into play.

Table 7 EK Key Metrics (Emirates 2015; CAPA 2014)

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fleet Size</td>
<td>231</td>
</tr>
<tr>
<td>Number of Pilots</td>
<td>3687</td>
</tr>
</tbody>
</table>
When the route has a flying time longer than the maximum allowed duty time of a crew member, the crew is augmented with an additional pilot who takes over for a portion of the flight while one of the pilots rests in one of the onboard crew rest areas. The pilot who has had a rest period may then operate the flight for a time period typically regulated at half the rest period, i.e., if on a 10 hour long flight a pilot rests for six hours, his duty time may be extended by three hours. For ultra-long haul operations like the Dubai-Auckland or Dubai-Sao Paulo routes, a fully augmented crew is required, i.e., there will be four pilots on board. An estimated breakdown of Emirates’ daily departures based on the number of crew carried on board is shown in Table X below. It can be inferred that for a day’s operations, EK needs 1120 pilots.

<table>
<thead>
<tr>
<th>Crew Strength</th>
<th>No. of Flts</th>
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</thead>
<tbody>
<tr>
<td>ULH Augmentation 4 crew</td>
<td>40</td>
</tr>
<tr>
<td>MH Augmentation 3 crew</td>
<td>100</td>
</tr>
<tr>
<td>SH 2 crew</td>
<td>330</td>
</tr>
</tbody>
</table>

When the route has a flying time longer than the maximum allowed duty time of a crew member, the crew is augmented with an additional pilot who takes over for a portion of the flight while one of the pilots rests in one of the onboard crew rest areas. The pilot who has had a rest period may then operate the flight for a time period typically regulated at half the rest period, i.e., if on a 10 hour long flight a pilot rests for six hours, his duty time may be extended by three hours. For ultra-long haul operations like the Dubai-Auckland or Dubai-Sao Paulo routes, a fully augmented crew is required, i.e., there will be four pilots on board. An estimated breakdown of Emirates’ daily departures based on the number of crew carried on board is shown in Table X below. It can be inferred that for a day’s operations, EK needs 1120 pilots.

Table 8 Emirates Crew Augmentation Breakdown Estimate

In SPO regimes, it can be assumed that even though only one crew member operates the flight with no assistance from the ground, the concept of crew augmentation may still be required. In architectures
where constant monitoring of the automation is required, it can be assumed that ultra-long haul (ULH) flights may be operated with three crew instead of four, medium haul (MH) flights with two crew, and short haul (SH) flights with 1 crew member on board. This would determine the new daily pilot need at 650 pilots, eliminating the need for 470 pilots. Conservatively estimating an hourly cost for the first officer at $180 (based on publicly available salary data plus estimates of benefits and margins), and using the average stage time of 6 hours 10 minutes, the daily savings can be worked out to be $521,982 or $190.5 million annually.

If we assume an architecture where constant monitoring is not required in cruise phase, and further assume that ULH flights can be operated with two crew and all other flights with one, this would eliminate the need for 610 pilots daily. This translates into a savings of $247.2 million annually.

<table>
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<tr>
<th>Table 9 EK Projected Savings Summary</th>
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<tbody>
<tr>
<td>Item</td>
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<tr>
<td>Total Revenue 2014</td>
</tr>
<tr>
<td>Total Expenditure 2014</td>
</tr>
<tr>
<td>Total Labour Expenditure</td>
</tr>
<tr>
<td>Lower estimate of annual SPO savings</td>
</tr>
<tr>
<td>Savings as a % of total expenditure</td>
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<tr>
<td>Savings as a % of labour expenditure</td>
</tr>
<tr>
<td>Higher estimate of annual SPO savings</td>
</tr>
<tr>
<td>Savings as a % of total expenditure</td>
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<tr>
<td>Savings as a % of labour expenditure</td>
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Comparing the savings as a percentage of labour expenditure between the two airlines, it can be seen that the short haul, all-narrowbody Southwest seems to have significantly higher projected benefits from moving to SPO. Even though the actual savings figure for Emirates will likely be better when using real world data instead of the conservative estimates of this analysis, it is unlikely that this gap may close.
This is not to imply, however, that SPO benefits short haul airlines more than long haul ones – that would require a detailed study of the costs across multiple airlines, not just convenient ones with relatively homogenous fleets like EK and WN.

### 3.2.2 Identifying New Costs

The promise of savings in labour cost is one of the big motivators towards moving to SPO. However, it must be recognized that, given the different architectural possibilities discussed so far, SPO may give rise to new costs due the needs of the operating architecture. It may be possible for small changes in the architecture to vary costs dramatically – for example, if a second pilot were to tag along on an SPO aircraft as a backup in case of pilot incapacitation as discussed in the literature (W. W. Johnson et al. 2013), the cost of operating the aircraft goes up compared to a true single pilot scenario, while the acquisition cost of the aircraft may come down marginally due to lesser system complexity. As such, it is important to identify potential sources of new costs that may be incurred by operators, and incorporate them when creating a baseline operations model. It is important to point out that this section will not discuss cost changes in aircraft systems (both acquisition and operation), since that cannot be considered new costs. Regardless of whether SPO happens or not, aircraft costs and capabilities will change over time as systems improve, and if not SPO, some other architectural change will drive that cost.

### New Operators

The first and most obvious new category for cost increases is the creation of new operators under the SPO architecture. These operators may be super-dispatchers, ground based pilots, ground based system specialists, or other ground based operators. When considering a move to SPO architectures, the cost of adding these new operators should be taken into account. A dedicated ground based pilot is likely to earn almost the same as an onboard pilot. In the USAF (DFAS 2016), a UAV pilot may make the same amount as a fighter pilot if they are of the same rank, though the fighter pilot has more opportunities to earn hazard based bonuses. Similarly, it can be envisioned that a ground based pilot would command the same salary as an onboard pilot of equivalent experience, but would not have an opportunity to earn
flight bonuses. If an architecture calls for a dedicated ground pilot for each flight, that would be more costly to operate than an architecture where a ground based pilot can be placed in charge of multiple aircraft, with the opportunity of getting backup when a plane needs dedicated assistance.

**New Infrastructure**

The second major driver of cost when moving to SPO is the need for new infrastructure. The involvement of ground based crew members in the loop will require ground based command and control stations to be built and operated. The number of required stations will vary depending on architecture. For instance, in a harbor pilot type concept (Koltz et al. 2015), ground stations may only be required near major airports. A dedicated ground pilot architecture on the other hand, would require ground stations based on the range of communications relative to the length of the flight. Comparisons of architecture must include infrastructure costs as part of the criteria.

**Pilot Shortage**

The introduction to this thesis mentions pilot shortage as one of the motivations for moving towards SPO. However, the problem of pilot shortage cannot be treated as the simplistic notion that a reduced need for pilots under SPO would match supply and demand. According to a study conducted at the University of North Dakota (Higgins et al. 2013), the US alone faces a cumulative shortage of 35,000 (against a cumulative need of 100,000) pilots until 2030. While single pilot aircraft will certainly require less of a labour force to operate, the effect on shortage may not be linear. Placing a pilot in sole control of an aircraft may require higher training expenditure, especially if the requisite minimum hours to qualify for command go up. This would also mean a more difficult path to a flying job for would-be pilots, which may further decrease the attractiveness of flying as a profession, and increase operating costs by pushing salaries upwards. These are trends worthy of consideration when choosing an SPO architecture, and further studies will be required to analyze the sensitivity of pilot shortage to changes in the flight operations architecture.
4. DEFINING A FLIGHT OPERATIONS BASELINE

4.1 Introduction and Goals

One of the distinct features of multi-crew operations, be it two, three or five persons up front, is the ability to divide tasks. In the system of systems (humans and automation) that is the flight deck, more people meant more interfaces, and more chances of a breakdown. In today’s two-man flight deck, Crew Resource Management Principles are used to divide work in a manner such that each individual pilot’s workload is manageable, while fostering cultural and environmental factors that mitigate the chances of a breakdown in the human-human interface. While operating a typical flight, as seen decomposed in Figure, the flight crew face decisions at various stages of flight. The first level decomposition of a typical two man flight operation is into five stages as seen in Figure 9. This will serve as the starting point for developing a notional baseline model of the flight operations process in two man conditions, which can later be adapted to SPO. At a second level, each of these stages are decomposed based on key decisions that roughly correspond to sub-stages. For instance, the decomposition of ‘pre-flight’ to a second level is fairly predictable and repeatable, while the decomposition of ‘cruise’ often varies in type and number of actions, and is an approximation. Digging deeper, each of these decisions is part of a process, and each decision impacts or interacts with a set of subsystems, based on the phase of flight and crew intentions.

The goal of building a baseline model of today’s flight operations is to enable comparisons of future SPO architectures. In the chapters covered so far, a few key factors have been identified as having an impact on architectural decisions. It is assumed that in the iron triangle of constraints that are constituted by safety, cost, and performance, requirements imposed by certification standards would act as a stabilizing factor of sorts to ensure a minimum level of performance that all architectures would be expected to meet. Hence, safety and cost related characteristics will be the key drivers of architectural decisions at a high level.
In order to enable a comparison on these parameters, it is important to first take a look at what drives cost and safety. As identified in the viability chapter, safety is driven by the pilot workload as well as the ability to handle off-nominal situations. Cost is driven by the increase in complexity, reliability, and redundancy of aircraft systems driving acquisition costs, and the amount of operators and infrastructure driving operation costs. A baseline model would take into account these factors, and enable comparisons accordingly.
4.2 Approach and Assumptions

4.2.1 Workload

Harris et.al. (Stanton, Harris, and Starr 2015) have mapped out a social organizational cooperation analysis contextual activity template that describes the interactions and cooperation between various elements of the sociotechnical system within flight operations today, as seen in Table 10.

In Table 10, the circles with arrows emanating from them describe the situations under which a function is typically performed, while the boxes with dashed lines indicate the range of possible phased where the function can possibly be performed. This can be considered as a good starting point to map out workload experienced by the pilots on board in today's operations.

By placing coloured indicators against each function, with each colour denoting the roles of actors involved in performing said function, the division of tasks amongst the different actors performing them can be mapped out, as seen in Table 11. This can then be repeated for each architecture generated. The change in the number of tasks allocated to the pilot flying can be considered as indicative of his overall workload. Comparing this change against the number of tasks in today's flight operations (as mapped in Table 11), a notional score can be generated for pilot workload.
Table 10 Social Organizational Cooperation Analysis - Contextual Activity Template (Stanton, Harris, and Starr 2015)

<table>
<thead>
<tr>
<th>Situations</th>
<th>Functions</th>
<th>Standing</th>
<th>Push-back</th>
<th>Taxi</th>
<th>Take-off</th>
<th>Rejected Take-off</th>
<th>Initial Climb</th>
<th>Climb to Cruise</th>
<th>Cruise</th>
<th>Change of Cruise Level</th>
<th>Descent</th>
<th>Holding</th>
<th>Initial Approach</th>
<th>Final Approach</th>
<th>Go-around</th>
<th>Landing</th>
<th>Emergency</th>
<th>Descent</th>
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</thead>
<tbody>
<tr>
<td>Attitude of aircraft</td>
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<tr>
<td>Altimeter</td>
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<td>Rate of climb or descent</td>
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Using the measurements in the study of heart rate variance in phases of flight by Wilson (Wilson 2002), weights may be assigned for the notional score of workload in different phases of flight, as compared...
against today's baseline. It should be noted that the analysis looks at the predicted increase in workload for a given architecture – it does not take into account the various systems that can mitigate it. This is due to two reasons – one, this is a high level process based approach that does not get into specific solutions and their capabilities to manage workload, and two, it is somewhat rigidly tied to today's operations model and does not allow room for completely new processes to take their place in the picture. Limitations of the approach are discussed further in the conclusions chapter.

4.2.2 Off-Nominal Scenarios

The ability to continue operating safely in a wide range of off-nominal situations is key to safe aircraft operations. When moving to SPO, it is important that the architecture be resilient to the challenges thrown by off-nominal situations. In building a baseline model of today's flight operations, a few key assumptions need to be listed. While there are any number of possible situations an aircraft can encounter, pilots typically do not train for all of them. The quick reference handbook, which usually contains checklists for abnormal and emergency situations, is a good starting point for listing out off-nominal situations that pilots train for. For the purpose of this analysis, it is assumed that today's operations present an acceptable level of safety in off-nominal conditions. Hence, to move to SPO, only off-nominal conditions unique to single crew operations will be considered when assessing safety of architectures.

As seen the literature, the primary concern here is the failure of the pilot itself. As such, the primary concern will be the ability of the architecture to deal with pilot incapacitation scenarios. Pilot incapacitation also makes a few other functions more critical. For example, communications failure (both datalink and voice) become more critical. Under today's operations, a communications failure does not necessarily imply a safety of flight issue – there are SOPs in place to manage such a failure. In single crew operations, depending on the architecture, a communications failure might imply an immediate diversion. Similarly, any architecture that involves autonomous flight abilities as a backup against pilot incapacitation would conceivably require immediate diversion in case of a degradation of such capabilities in flight – for example, the failure of an air data computer might degrade speed accuracy
below levels acceptable for auto flight. To comparatively evaluate architectures, a notional score would be given to each architecture based on the feature of the architecture that will be instrumental in negating a pilot incapacitation scenario. Analysis will assume systems are capable of detecting all forms of incapacitation.

A third concern is the ability of the pilot to deal with multiple failures. In today's operations, crew coordination during a failure is part of the operational training imparted to pilots. A standard model of crew coordination during a failure event can be seen in Table 12 (Airbus 2015). While there are a large number of possible failure combinations given the number of systems in modern aircraft, the model will be limited in this regard, looking at this issue only at a very high level. The scoring here would be notional, based on expert judgement of the ability of a pilot to handle multiple system failures in a given architecture. For example, an architecture that has a second pilot tagging along would be deemed safer than an architecture that has a ground based crew member with access to the aircraft systems, which in turn would be deemed safer than an architecture with only the automation supporting the pilot.
Table 13 Off Nominal Situations - Criticality in Phases of Flight and Sum of Actions Required (Airbus 2013)

Table 13 illustrates the off-nominal situations covered in the quick reference handbook used by Airbus A320 pilots (Airbus 2013). This table has been constructed by listing the off-nominal situations covered by the handbook, identifying the number of checklist actions and memory items, and assigning a severity based on expert judgement. On average, pilots face 9.7 checklist actions and 2.6 emergency actions for an off-nominal situation. The checklist actions are typically divided between the two pilots (we assume an equal division here), while emergency actions are memory items usually performed by the PF. While automated checklist systems or a second non-functioning pilot can alleviate some of the workload incurred in performing checklist actions for a single pilot in off-nominal situations, the memory items will remain with the pilot himself. It can be reasonably assumed that the amount of memory items may not increase in the move to SPO, since it is in essence a single pilot’s function today.

In evaluating the ability to deal with combinations of failures, it is evident that systems exist which can prioritize emergency actions into a single checklist (Roger M. Records, John A. Taylor, William D. Shontz 1994). These actions are performed in sequence, and not in parallel. The factor in parallel is the addition of manual flying – in off-nominal situations where manual flying is required, there is added workload that comes from monitoring the basic flight parameters. From Table 13, it can be seen that there are at least 18 instances of off nominal situations where manual flying is necessary – though this is not to say that the remaining off nominal situations are mutually exclusive with manual flight.

To compare architectures, a notional score would be given to each architecture for its ability to handle incapacitation. Three off-nominal combination scenarios, or ‘corner cases’ will be assessed subjectively for workload. These are Dual Engine Failure + Ditching, Avionics Smoke + Emergency Descent, and Landing with Abnormal Landing Gear + High Engine Vibration. The first two scenarios are logically connected, while the third is not. All situations involve manual flying.

Combining this score with the score assigned for pilot incapacitation will indicate the total ability of the pilot to handle off nominal situations in each SPO architecture. The analysis will treat pilot incapacitation and the three corner cases with equal weightage, and will not include any other conditions in combining
the scores. In the conclusions section, extreme corner cases – scenarios the architecture has no reasonable way to deal with – will be identified and discussed qualitatively at a high level.

4.2.3 Acquisition Costs

In moving to SPO, it is reasonable to assume that aircraft systems present today would need to be made more reliable, redundant, and robust. It is also clear from the concepts discussed in the literature reviewed that additional systems will also need to be created (Stanton, Harris, and Starr 2015). All of these can be expected to increase the acquisition costs of an SPO aircraft compared to today’s two crew aircraft. In order to evaluate architectures, it is necessary to compare the relative acquisition costs of various architectures. The baseline model will enable this comparison by attempting to identify changes in complexity of aircraft systems.

Cahill, et. al, (Cahill, McDonald, and Losa 2014) propose a sociotechnical model of the flight crew task in their study involving crews from European airlines, and use process gates to define sub-phases in the flight operations process. They use the framework shown in Table 15 to define decisions taken at these process gates. The framework is also useful for mapping out human-human and human-system interactions at a sub-phase level. Expanding this model, it is possible to create a list of systems that the crew interact with at each phase of flight, as seen in Table 16. When the first officer in the baseline model is replaced with a ground pilot or on-board automation (or a combination of both), it is possible to judge what systems need more capability, reliability, and redundancy. This can be done by looking at the change in the level of autonomy for each component system under different architectural choices. To quantify this difference in level, a hierarchy of automation as shown in Table 14 can be used (Endsley and Kaber 1999). For each system moving one level up the hierarchy, it can be assumed that the total avionics cost of the aircraft moves up by an arbitrary figure – 2.5%, for example. This will not take into account the relative complexity of different systems, and hence must be considered a limitation of this analysis. All comparisons will be made on a notional aircraft with a value of $100 million for narrowbodies, and $200 million for widebodies, with an assumed avionics cost share of 35% of total cost.
It is also possible to use the same expanded sociotechnical model to identify phases where new systems may be required, when new players and functions are brought in to replace the F/O. A new system added will cost more than a system which needs to be made redundant, which in turn may cost more than a system which needs to improve in reliability. A complexity score may then be assigned based on the number of new systems added.

Table 15: Hierarchy of Levels of Automation (Endsley and Kaber 1999)

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<th>Level of automation</th>
<th>Monitoring</th>
<th>Generating</th>
<th>Selecting</th>
<th>Implementing</th>
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<tr>
<td>(1) Manual control (MC)</td>
<td>Human</td>
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<td>(2) Action support (AS)</td>
<td>Human/Computer</td>
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<td>(3) Batch processing (BP)</td>
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<td>Human/Computer</td>
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<td>(4) Shared control (SHC)</td>
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<td>(6) Blended decision making (BDM)</td>
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<td>Human/Computer</td>
<td>Human/Computer</td>
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<tr>
<td>(7) Rigid system (RS)</td>
<td>Human/Computer</td>
<td>Computer</td>
<td>Human</td>
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Table 14: Process gates in a typical flight operation (Cahill, McDonald, and Losa 2014)
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<td>Review/accept</td>
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<td>Aircraft ready - technical register of airplane</td>
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<td>Cabin ready to board</td>
<td>Cabin Crew</td>
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<td>Flight execution</td>
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<td>Push back / engine start</td>
<td>Out of gate/off blocks</td>
<td>Engine start CL (15)</td>
<td>APU, Electrics, ECAM (fuel, doors),</td>
<td>Radio comms, CL support for capt systems</td>
<td>AS</td>
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<td>Taxi</td>
<td>ATC Ground</td>
<td>Pre-departure CL (17)</td>
<td>Electrics, Hydraulics, Brakes, ECAM, APU, Flight Controls</td>
<td>Radio comms, CL support for capt systems</td>
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<td>Takeoff</td>
<td>ATC Tower</td>
<td>Before TO CL (17), Callouts, TO decision</td>
<td>Brakes, Electrics, Engines, Xpdr (TCAS)</td>
<td>Radio comms, SOP callouts &amp; actions, CL support for capt systems</td>
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<td>Climb</td>
<td>ATC Departure</td>
<td>After takeoff CL (18)</td>
<td>Engines, Hydraulics, Electrics, Autopilot (LNAV, VNAV)</td>
<td>Radio comms, CL support for capt systems</td>
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<td>Cruise</td>
<td>ATC Enroute</td>
<td>Automation interactions</td>
<td>Autopilot inputs, ACARS (route amendment, company comms, Wx)</td>
<td>Radio comms, FMC programming, monitor automation</td>
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<td>18</td>
<td>1000 ft/sterile cockpit</td>
<td>ATC Approach</td>
<td>Briefing, Before landing CL (16)</td>
<td>Cabin environment, ECAM (Nav), Electrics, Hydraulics</td>
<td>Radio comms, CL support, SOP actions</td>
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<td>1000 ft/3-4 miles before landing</td>
<td>ATC Tower</td>
<td>Autoland decision</td>
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<td>Decision height</td>
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<td>Callouts</td>
<td>Hydraulics, FMC (Alt), Electrics</td>
<td>Radio comms, CL support, SOP actions</td>
</tr>
<tr>
<td></td>
<td></td>
<td>24</td>
<td>Landing and rollout</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>25</td>
<td>Taxi</td>
<td>ATC Ground</td>
<td>After landing CL (8)</td>
<td>Hydraulics, Engines, Xpdr, Electrics, Brakes, APU</td>
<td>Radio comms, CL support, SOP actions</td>
</tr>
<tr>
<td></td>
<td></td>
<td>26</td>
<td>Park and shutdown</td>
<td>ATC Ramp</td>
<td>Parking CL (7), Securing aircraft CL (9)</td>
<td>Brakes, Engines, Electrics, ECAM (Fuel), FMC (Air Data, Nav), APU</td>
<td>Radio comms, CL support</td>
</tr>
<tr>
<td>Postflight</td>
<td>Flight report</td>
<td>27</td>
<td>Flight report</td>
<td>Maintenance</td>
<td>Safety, Maintenance report decision</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Change aircraft/prepare for next flight</td>
<td>28</td>
<td>Change aircraft/prepare for next flight</td>
<td>Scheduling</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Numbers in brackets () indicate number of checklist items, based on A320 normal operations checklist. CL stands for checklist. Some checklists have been combined for better alignment with process gates in this model.
4.2.4 Operating Costs

A key driver for the move to SPO, as discussed in the introduction to this thesis, is the potential savings in labour costs. In the viability analysis section, the potential cost savings for two airlines were also discussed. Different airlines have different operating contexts, leading to different architectural needs, and hence different levels of savings. As discussed previously, new costs may be incurred in SPO due to new types of crew members and infrastructure being required. The baseline model will compare operational costs between architectures with the help of a few key assumptions.

Costs will be calculated on the basis of a notional airline with 300 aircraft, which is a number close to the US average airline fleet size. 12 pilots per aircraft are assumed for a narrowbody fleet and regional jet fleet, and 10 for a widebody fleet. Average annual pay is assumed to be of $150,000 for narrowbody pilots, $110,000 for regional jet pilots and $190,000 for widebody pilots. Three stage lengths – 1.25 hours, 2 hours, and 9 hours – representative of a regional jet, narrowbody and widebody fleet will be used. For narrowbodies, four departures per day will be assumed, and for widebodies, 1.5 departures will be assumed, and for regional jets 7 departures per day will be assumed. For simplicity, the analysis will not take into account spare aircraft, or aircraft in down time for maintenance, and will assume full fleet utilization. For ground based crew members who are effectively pilots, the pay will be assumed to be the same as that of an on-board pilot, regardless of the number of aircraft they are responsible for. This is in line with UAV pilot pay compared to fighter pilot pay scales in the US Air Force (DFAS 2016). In concepts that require a non-functional pilot to be on board, it would be assumed that the non-functional pilot is on half-pay during the time he is on board and not flying. All of the above will be used in determining costs on an annual basis.
5. ARCHITECTURAL DECISIONS

4.1 Introduction

This section of the thesis aims to introduce and expand the SPO concepts currently being discussed in the available literature. The literature describes concepts that aim to establish a reasonable transition from today's two crew operations to single pilot operations with a minimum of disruptions. This has been the case historically when reduced crew operations were introduced, with no major disruptions in the progressive moves from five to two crew. And following the fate of the radio operator, navigator, and flight engineer, the concepts focus on the replacement for the first officer - be it through automation, or through a remotely located human.

From the literature review, it can be seen that while many concepts are described at a high level, they have not all been described or investigated to the same level of granularity. This thesis will not investigate these concepts at a high level of detail, but will aim to investigate them by scoring them on a notional basis which levels the field. The scoring system will use the methods presented in the previous chapter which describes today's two crew operations, and by plugging in the replacement for the first officer under each architectural scenario, work out the predicted increase in complexity of systems affected by the architecture described. In the final trade space analysis, there may be more options than listed under this section. This is due to the fact that some elements of the architectures described in this section are interchangeable, and allows for some concept permutations.

It is also necessary, at this point, to restate a couple of assumptions made in earlier chapters. The ability to deal with pilot incapacitation will not be parsed into different levels - for example, if some architectures call for on board incapacitation detection systems, it will be assumed that they all have the same capabilities. Similarly, the use of video will not be considered as a factor. Some of the architectures take into account the increase in complexity caused by the higher bandwidth required by features such as video, however video usage itself is a solution specific case of using that bandwidth, and cannot be considered as an architecturally distinguishing feature.
Based on the literature review, the following architectural decisions were identified:

- **Automation**: The duties of the first officer are taken on by additional automation as well improvements to the capabilities of current systems.
- **Virtual pilot**: Assumed as the highest form of automation, a virtual pilot or avatar fully capable of autonomous flight in emergency situations.
- **Ground based pilot**: The first officer in these architectures will be replaced by a pilot capable of supporting the on board pilot or flying the aircraft while based on the ground. This group also includes the concept of a super dispatcher who has limited interactions with the aircraft systems.
- **Harbor pilot**: This concept involves the use of a ground based pilot only in the terminal stages of flight, similar to how harbor captains guide large ships in and out of busy ports.
- **Tag along pilot**: This variant of concepts involves a second non-functional pilot travelling on board as a backup to the single pilot.
- **Wingman**: The wingman is a concept where pilots of nearby airborne aircraft can provide limited assistance to a single pilot in off-nominal or high workload conditions.
4.2 Concept Group 1: Automation Replaces the First Officer

Description: This group of concepts sees the duties of the first officer completely replaced by automation. There is no other person involved, either in the air or on the ground, apart from the single pilot in command of the aircraft. The pilot interacts with the automation, which supports him in performing the tasks required to safely operate the flight. The pilot interacts with the aircraft systems with support from the automation, and plays the role of a manager of systems, except in the case of an automation failure. It is expected that this interaction shall be facilitated by enabling technologies, such as voice recognition, reliable datalinks and communication technologies. It is also envisioned that a lot of these interactions make take place through multi-modal means, with more annunciation and interactivity on the head-up display, since the pilot would be expected to spend as much time flying head-up as possible. The pilot also interacts with ATC as well as company or dispatch, through voice and
datalinks. ATC and dispatch are expected to support and provide knowledge aids in making strategic decisions like route planning. The automation can also interact with ATC and dispatch, though these interactions would not amount to direct control of the aircraft in most scenarios, and would typically be limited to the exchange of information and messages. An example of such an interaction would be dispatch sending an amended route directly to the FMS.

In the event of pilot incapacitation, the expectation is that the aircraft can recover automatically by flying itself to the nearest suitable airport and landing there. It is also expected, in this concept architecture, that the aircraft can detect pilot incapacitation to a reasonable extent. This concept is alluded to in the literature reviewed (W. W. Johnson et al. 2013), and has two concerns identified: potentially increased pilot workload and the ability of the aircraft to deal with incapacitation in reality. The effects on the pilot pipeline for airlines is also unclear. This concept may require relatively inexperienced pilots to be put in sole charge of an aircraft, which may lead to regulators requiring a higher number of hours in command before such an action can be taken, which in turn can exacerbate pilot shortage by raising the barriers to entry for flying as a career. Another anticipated regulatory hurdle is the need to experimentally demonstrate that the single crew member does not face higher mental workload than either member in today’s two crew operations. It is assumed that this would be a tougher goal for architectures that do not involve a second human in the loop in any form, and replaces them with automation alone.

4.2.1 Variant 1: Tag along Pilot

Description: A variant for this concept envisions two pilots on board as an augmented crew. In the literature (W. W. Johnson et al. 2013), Prof. Hansman of MIT describes the notion that a second non-functioning pilot may be placed on board for safety reasons in case of incapacitation. The idea as described by him envisions pilots who are commuting to and from their bases, deadheading or positioning pilots being present on board for every flight. This concept, as he concedes in the literature, would place challenges on airline crew scheduling, and may be dependent on the scale of the airline.
In the variant of this concept envisioned here, only one pilot will fly the aircraft at any given time, and the other is merely ‘deadheading’. This concept variant involves a change in airline scheduling. Two pilots are dispatched as a crew, similar to today’s operations, but the spare pilot on board will be considered to be resting (an appropriate space may be designed for the same, not dissimilar to today’s crew rest areas, but with direct flight deck access). When the first pilot times out under FDTL, the second takes over, and the first moves to rest. Since current FDTL regulations allow for half of the on-board time to be counted as extended flight time (Federal Aviation Administration 2011), an FDTL of ten hours for the first pilot allows the second to fly for five more. As a result, a two man crew can be sent on a duty cycle that is 50% longer than today, when their duty cycles are exhausted in parallel. The second man available on board at all times negates the requirement for dealing with pilot incapacitation, and the second pilot can be the equivalent of today’s first officer and paid accordingly - the former reduces acquisition cost for the airframe and the latter reduces operating costs compared to today while maintaining the pilot pipeline.

4.2.2 Limitations

This group of concepts has some limitations which cannot be addressed. It is likely that the architecture would involve, at some level, the automation managing the systems, with the pilot providing strategic inputs and knowledge. While it is possible to build in capability to recover the aircraft if the pilot fails, it may not be possible if the scenario is reversed. A single pilot in a Qantas 32 type scenario with multiple failures, especially the failure of the automation that manages systems, is unlikely to meet with a positive outcome. Additionally, pilot incapacitation combined with any failure that degrades auto flight capability – unreliable speed indication, or air data computer failure, for example – may also not be possible to recover from. This concept is also the one that is most vulnerable to deliberate malicious pilot action like the GermanWings crash.
4.3 Concept Group 2: Single Pilot Assisted by Virtual Co-pilot

**Description**: This group of concepts describes a single pilot flying the aircraft, aided by a virtual co-pilot. A cognitive machine assistant called CASSY (Cockpit ASsistance SYstem) was test flown in the late nineties by the German Deutsches Zentrum für Luft- und Raumfahrt on their VFW-614 test aircraft (Onken 1997). The study demonstrated that a virtual cognitive assistant can provide a more complete picture of situational awareness, albeit in two crew operations. In this group of concepts, it is assumed that these results would basically hold true for SPO as well, though the total situational awareness may be decreased marginally due to the absence of the second crew member (or constraints placed on the second crew member operating remotely).

When the second pilot is replaced by automation, one key aspect of today's flight decks disappears — social interaction. While concepts that include a ground or air based human crew member do not suffer
from this issue, a single pilot operating long flights would be affected by boredom. Additionally, the single pilot who is monitoring a greater number of systems than a pilot in today's two crew operations may find it difficult to process the volume of information involved, and a virtual co-pilot may play a role in presenting information distilled into actionable forms via multimodal interactive means. This concept would require extensive use of voice recognition, speech-to-text and text-to-speech technologies, with the ability to operate reliably regardless of accent and other speech variations, as well as high ambient noise. An example of this kind of a system could be the virtual copilot, when faced with multiple system failures, notifying the pilot of the same via aural warnings, and then, when commanded by the pilot, commencing a prioritized checklist similar to a first officer today. Checklists may also be redesigned, with the human pilot approving some actions (today's memory items, for instance) and the automation handling other actions which have lesser impact on safety.

Under this concept, the pilot will interact with ATC and other ground based entities like dispatch via voice and datalink communications. These would scenarios would remain largely unchanged from concept group 1. The virtual copilot can interact with ground based entities via datalink, though these interactions will mostly be limited to automated reporting (position reports and other status reports) under nominal conditions. Under off-nominal conditions, the virtual co-pilot may undertake limited external voice communications as well, especially when triggered by checklist actions or to announce intentions over a frequency when undertaking emergency actions. It is assumed that the virtual copilot would be capable of detecting an incapacitated pilot and be able to automatically recover the plane in such a case. The voice interaction between the pilot and virtual co-pilot may provide more opportunities for technology to detect subtler forms of incapacitation, like strokes for example.

4.3.1 Variant 1: Tag along pilot 2

Description: Similar to concept one, a second pilot may be placed on board as a fail-safe against incapacitation. Under this variant, it can be assumed that the virtual pilot does not need auto flight capabilities, but retains all other characteristics. The operating costs and acquisition costs would be expected to change in a manner similar to the previous concept, though the acquisition cost in absolute
terms would be higher for this concept compared to concept group 1 due to the increased complexity in technology required to enable a virtual co-pilot.

4.3.2 Limitations

The limitations described under the previous concept are applicable in this case, and perhaps exacerbated by the nature of this architecture. With a virtual pilot, the pilot flying is even more reliant on automation for routine flight tasks. Hence, a failure of the automation that acts as the agent that manages multiple systems may end up being a scenario from which recovery is unlikely. This concept can also be deemed vulnerable to deliberate malicious pilot actions, but less so than the previous concept due to the assumption that the virtual pilot will have better detection capabilities.

This concept will also deal poorly with multiple failures involving the human machine interface. If voice recognition fails along with a major system, the pilot will be forced to rely on head-down interaction with the systems to manage the problem, at the cost of situational awareness. If the aforementioned major systems failure is one that needs him to take over manual control of the aircraft, it places him in an impossible situation where he has to perform head-down check list actions while flying the aircraft head-up.
4.4 Concept Group 3: Ground Based Assistance

**Description:** This group of concepts includes ground based crew member(s) assisting the pilot on board in performing flight tasks. The addition of a ground based crew member is the architecture that has seen the most investigation based on the literature review (W. W. Johnson et al. 2012; Lachter et al. 2014; Stanton, Harris, and Starr 2015; Koltz et al. 2015). The pilot interacts with the aircraft automation, ATC, dispatch, and the ground based pilot. The duties of the ground based crew member(s) vary based on the architecture of each concept variant. The ground based crew member(s) can be a constant companion to the on-board pilot, or an assistant who comes on when workload is high, or a facilitator who manages specialists who assist on an as-needed basis. The ground based crew member(s) can split duties with the on-board automation, with a variety of split options possible. The ground based crew member(s) may or may not have the option of taking over control of the aircraft in a pilot incapacitation scenario, depending on the concept variant. Depending on architecture, these concepts may see a need for more
robust voice and data communication systems. In the event the connection with the ground is lost, the pilot may need to recover to the nearest airport if auto recovery capability is absent.

4.4.1 Variant 1: Constant Companion – Human Centric (Dedicated Assistance)

Description: In this variant, the aircraft will have dedicated ground based crew member(s) assisting for the entirety of the flight. The assistance may be provided by one crew member or many, depending on the length of the flight. According to a San Jose State University study (Brandt et al. 2015), the initial situational awareness of a ground based operator is not relevant if adequate displays provide an opportunity to gain situational awareness, making transfer of duties between ground crew members feasible. The study also states that specialist crew members on the ground were slightly more preferred than a general super-dispatcher type person, though both types of crews were feasible for SPO. For long haul operations, depending on architecture, multiple enroute ground stations may need to assist the aircraft.

In this variant, the pilot on board flies the aircraft and interacts with the on board automation, ATC, and the ground crew member. Under the human centric variant, the bulk of the duties of the first officer would be shifted to the ground based crew member(s) who will assist the on board pilot for the entire flight. Architecturally, this would require robust high bandwidth communication systems, and UAS type capabilities. The ground based crew member(s) shall take command of the aircraft in case of pilot incapacitation being detected (by on-board systems or the ground based crew), and fly the airplane to a landing. The ground based crew member(s) shall assist the pilot in emergency situations, though further study would be needed to precisely define the nature of the assistance. In some situations, it may be desirable to have the ground based crew member fly the aircraft while the pilot manages ECAM or checklist actions (e.g., stable flight but fuel system develops an issue which needs pilot’s attention to investigate). In others, it may be desirable to have the pilot fly while the ground based crew manages the problem (e.g., One engine failure, pilot can hand over ECAM actions to the ground after (s)he performs memory items from the checklist, allowing the pilot to focus on securing the aircraft). The
ground based crew member also maintains an appropriate level of interaction with the on board pilot, eliminating boredom and providing the social pressure to perform duties diligently.

This concept may not be the best for maximizing cost savings from SPO. The need for a constant companion on the ground may require the same number of pilots as today. However, they may be paid lesser than flight duties, which could see some savings. Another option is to have on-board pilots serve periods of duty on the ground, based on seniority. The pilot pipeline for airlines will not see significant change in this concept, because the ground based crew member could eventually have a path towards qualifying as an on board pilot, or captain.

4.4.2 Variant 2: Constant Companion – Automation Centric (Super Dispatcher)

Description: This variant is similar to the one described previously in terms of overall architecture. The key difference is that the on board automation takes a greater share of the duties of the first officer. The ground based crew member mostly performs monitoring duties, and may monitor more than one flight at a time. The ground based crew members will work in a group with backup, and if an aircraft needs dedicated assistance, the ground based crew member responsible for the aircraft will hand over all other aircraft under his control to other operators and turn his full attention to the aircraft in need. In effect, there will be a ground based crew member available to the aircraft throughout the flight, though the level of availability will vary.

The ground based crew member may play a role in detecting pilot incapacitation (along with the on board means of detection), but will not be able to ‘fly’ the aircraft to a landing. Instead, they may be able to command the aircraft to perform an auto recovery. In case of emergency or off-nominal situations, the ground based crew member will act as a monitor of systems, aid in strategic decision making, and act as a knowledge base for the on board pilot to consult. Checklist actions may be limited to reading out challenges, and noting whether changes on the ground control station displays are consistent with the pilot’s expected responses. Use of video streaming from the cockpit to the ground may be required in this architecture.
The ability of a ground based crew member to handle more than one flight concurrently makes it possible for this architecture to save more in operational costs. Similar to the prior variant, inexperienced low time pilots may be cycled through periods of ground crew duty before they are placed in command of an aircraft. A fraction of pilots from the total pilot pool can be detailed for ground duty similar to how pilots are placed on hot reserve today.

4.4.3 Limitations

These concepts are dependent on reliable communications capabilities. While redundancy is possible, single point of failure issues like the satellite malfunctioning could become a problem. This combined with pilot incapacitation would provide a scenario from which a positive outcome is unlikely. Reliance on communication systems also poses a security problem, like the incident where Iran captured a US RQ-170 drone by ‘fooling’ its communications systems (Lateef Mungin 2013).

4.5 Concept Group 4: Need Based Assistance

Description: This group of concepts describe architectures where a human external to the flight operations process, be it on the ground or elsewhere, assists the pilot in operating the flight in situations when the pilot needs it.

4.5.1 Variant 1: Harbor Pilot

Description: This variant describes a concept where a ground based crew member assists the pilot in arrival and departure. The ground crew member will typically be based at or near an airport, and assist the pilot in navigating the traffic dense airspace in the terminal, approach and departure airspace. Studies show that pilots typically encounter the highest workload during takeoffs and landings (Wilson 2002), and hence these phases of flight are ideal for remote assistance in SPO. Since most of cruise flight
today is conducted by the autopilot with the two pilots on board monitoring systems and managing communication, a similar regime will continue under this variant wherein the onboard automation shares the monitoring workload, and assists in communication via datalink. The pilot interacts with the automation as well as ATC and possibly dispatch, while the automation’s interaction with these entities is limited to communication during cruise flight. In the arrival and departure stages, the ground pilot may be able to take over control of the aircraft if needed. In a pilot incapacitation scenario, the onus falls on the onboard automation to detect incapacitation in cruise flight, and it then automatically flies the aircraft to the nearest airspace where a ground crew member can take over control, or supervise an autoland. The concept of a harbor pilot has been studied in some of the literature reviewed (W. W. Johnson et al. 2013; Koltz et al. 2015), and may be viewed favourably from the point of view of reducing operating costs. As with earlier concepts that involve ground based crew members, inexperienced low time pilots may initially start as ground based crew members before being promoted to the flight deck job.

Figure 13 Concept Group 4 Variant 1 System Diagram
4.5.2 Variant 2: Wingman

Description: The concept of a wingman has found brief mention in the NASA SPO Technical Interchange Meeting (W. W. Johnson et al. 2013). The concept entails airborne assistance from a ‘wingman’, typically an aircraft in nearby airspace. The wingman concept could theoretically be enabled by advances in communications and automation. When a flight encounters an off nominal situation, a nearby pilot whose aircraft is operating normally may provide assistance to the pilot in distress, though this would typically be limited to aiding in strategic decision making, and possibly assistance with checklist (it types match). While it can be argued that the concept of a wingman is not realistic as a standalone architecture, it could be added as a module to some of the other architectures proposed so far. For instance, in the harbor pilot concept, safety in cruise flight could be augmented by having a wingman, as opposed to completely unassisted flight.
As such, the cost impact of the wingman concept is not entirely clear. Acquisition costs for the airframe may move up marginally due to requirements for improved communications technology, though this may already be covered by the needs of ground based control as proposed in some of the earlier architectures. Additional training costs for the crew are also expected to be marginal, probably in the order of what it costs to train crews to perform In-Trail Procedures today.

4.5.3 Limitations

The harbor pilot concept leaves the aircraft open to the same issues as discussed in concept group 1, except only in the cruise phase where it is not in range of a harbor pilot. A catastrophic failure in cruise would require the aircraft to fly itself to a point within range of a harbor pilot who can then remotely pilot it down. However, similar to group 1, pilot incapacitation and a navigation failure combined could leave the aircraft in a situation where it cannot bring itself to a safe area.
6. ANALYSIS OF CONCEPTS

6.1 Heuristics and Constraints

To begin the analysis of the concepts described, the heuristics of decision making must be stated (Crawley, Cameron, and Selva 2015). The boundaries of the architectural space being considered here can be defined as the sum of possible architectural combinations derived from the decisions described in the previous chapter. These in turn are derived from the goal of reducing the number of crew members on aircraft used in commercial air transport operations from two to one. The impact of these decisions have been notionally quantified by trying to define the changes implied by comparing them against a baseline of today’s operations. The scope of the decisions is limited to single pilot operations alone, and does not explore continuous fully autonomous flight, for instance. Fully autonomy is explored only as a backup option. Similarly, at the other end of the spectrum, the decisions allow for two crew members to be present on board but only one operates the aircraft (Tag Along Pilot concepts).

The second heuristic as defined by Crawley, et. al., states that the decisions should significantly impact the metrics on which the architecture is being evaluated. In the following analysis, the evaluation is based on safety versus cost. This heuristic holds true for most of the decisions in the previous chapter, with the notable exception of the wingman concept. In the case of this concept, the costs involved are not immediately apparent, since the concept of a wingman can range from simple communications support all the way to coordinated procedures requiring significant changes in the air traffic system and scheduling – yet the role, at a glance, seems limited in terms of the benefits it can directly bring to SPO. However, the wingman concept may impact safety when combined with some of the other concepts, and hence it may be worth including this decision in the list.

The third heuristic states that the decision model should include only architectural decisions. In this regard, the list of decisions is simplified by the exclusion of secondary concepts. For example, the idea of on-ground detection of potential pilot incapacitation by screening for medical conditions is not included in the decision space since it does not change the architecture significantly. Similarly, the
potential roles played by other crew members like ground staff and flight attendants is also excluded from the decision space since these will also not have any significant architectural impact.

The architectural decisions listed in the previous section include some options that constrain each other. In Table 15, a matrix shows these constraints as they relate to each other. It must be noted that the constraints are not mutual in a lot of cases – for example, the presence of a Tag Along Pilot negates the need for a Wingman, but the presence of a Wingman does not necessarily negate the need for a Tag Along Pilot since the Wingman cannot cover all of the aspects of the role played by a Tag Along Pilot. It must also be noted that not all of these are hard constraints – some of them are soft constraints based on logical likelihood. The full list of constraints identified are as follows:

a. If a virtual pilot with autoflight capabilities is present, there is no need for a ground based dedicated pilot.
b. If a virtual pilot with autoflight capabilities is present, there is no need for a ground based harbor pilot.
c. If a virtual pilot with autoflight capabilities is present, it makes no sense to have a tag along pilot.
d. If a ground based dedicated pilot is present, there is no need for a virtual pilot.
e. If a ground based dedicated pilot is present, there is no need for a ground based harbor pilot.
f. If a ground based dedicated pilot is present, there is no need for a tag along pilot.
g. If a ground based dedicated pilot is present, there is no need for a super dispatcher.
h. If a ground based harbor pilot is present, it would preclude the use of a ground based dedicated pilot.

i. If a ground based harbor pilot is present, there is no need for a super dispatcher.

j. If a tag along pilot is present, there is no need for a virtual pilot with autoflight capabilities.

k. If there is a tag along pilot, there is no need for a ground based dedicated pilot.

l. If there is a tag along pilot, there is no need for a ground based harbor pilot.

m. If there is a tag along pilot, there is no need for a wingman.

When looking at these constraints, it can be seen that the Ground Based Dedicated Pilot excludes a lot of the other options, as does the Tag Along Pilot. However, it must be noted that these are both high cost options, where it would cost almost the same to operate the flight as it does today with two crew members. In essence, these concepts merely change the physical location of the second crew member from the right hand seat in the flight deck. The Automation concept does not appear to exclude any options – this is because the concept itself is a bit fuzzy. Varying levels of automation can be used in combination with all of the other architectural decisions, up to and including an auto recovery function. Virtual Pilot is separately defined as a form of Automation where full autonomous flight capabilities are assumed. This is for the sake of simplicity, and is cognizant of the fact that levels of autonomy may fall anywhere on a spectrum with far too many permutations and combinations possible. If the aircraft is capable of reliably flying in full autonomy in case the pilot fails, it can be assumed that all ground based flying roles are redundant.

The wingman concept, as described in the previous section, is not a role that is full-fledged enough to cover the functions of any other role in the other decisions. Hence, it does not exclude any other decision. However, it is excluded itself by the ground based dedicated pilot and the tag along pilot, since these can perform better than the wingman, who, it must not be forgotten, must manage his own aircraft while assisting any others. Similarly, the super dispatcher concept has comparable constraints of being a not full-fledged role where the duties are limited under normal conditions to monitoring multiple aircraft which limits the amount of interaction with any given aircraft.
When combining these decisions into architectures, it must be kept in mind that the combinations used must replace the first officer’s roles and functions in its entirety. Hence, one of Automation, Virtual Pilot or Ground Based Dedicated Pilot must be a part of Based on these constraints discussed above, the following possible combination of architectural decisions has been computed:

Table 18 List of Possible Architectural Combinations

<table>
<thead>
<tr>
<th>Combinations (Denotation)*</th>
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<tbody>
<tr>
<td>1</td>
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<tr>
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<td>12</td>
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<tr>
<td>13</td>
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<tr>
<td>14</td>
</tr>
</tbody>
</table>

* - (Suffixes of (n), (w), and (r) are added when comparing for narrowbodies, widebodies, and regional aircraft.

The next step is to use the scores computed by comparing against the baseline. The scores in the previous chapter are for individual decisions – for combining them into architectures, care must be taken to avoid duplication. For instance, the architecture denoted by AGdW has a dedicated ground based pilot as well as an airborne wingman provision. Both of these require advanced communication technology, and hence the higher cost or safety score may be considered instead of counting both scores. Using the scores computed in the comparison against the baseline as described in the previous chapter, these combinations produced the following scores for narrowbodies, widebodies, and regional aircraft, as seen in Table 19.
### Table 10: Summary of Savings and Score for all Architectures

<table>
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<th>Scenario</th>
<th>A(w)</th>
<th>AGd(w)</th>
<th>ASW(w)</th>
<th>AT(w)</th>
<th>V(w)</th>
<th>VT(w)</th>
<th>YS(w)</th>
<th>ATS(w)</th>
<th>GdW(w)</th>
<th>AGdW(w)</th>
<th>AGhW(w)</th>
<th>AGh(n)</th>
<th>AGh(r)</th>
<th>AGhW(n)</th>
<th>AGhW(r)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual Wage Savings</td>
<td>$285,000,000</td>
<td>$22,325,000</td>
<td>$239,400,000</td>
<td>$252,510,000</td>
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| Workload Score | 21.3 | 26.1 | 21.3 | 21.3 | 21.3 | 24.9 | 24.9 | 26.1 | 26.1 | 22.9 | 22.9 |
| Off-nominal Score | 21 | 39 | 32 | 21.5 | 32.5 | 50 | 28.5 | 50 | 37 | 39.5 | 34.5 |
| Cumulative Safety Score | 42.3 | 65.1 | 53.3 | 42.8 | 53.8 | 71.3 | 53.4 | 74.9 | 61 | 61.1 | 65.6 | 56.9 | 57.4 |

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<th>V(n)</th>
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6.2 Discussion of the Trade Space

The cost savings and safety scores obtained by comparing the architectures against a baseline formed by today’s operations can be plotted in a tradespace as shown in Figure 15. Safety and cost are in tension, as can be seen in the figure. Architectures with higher inherent safety characteristics are more expensive to operate on an annual basis. In the tradespace above, the orange data points denote narrowbody architectures while the yellow points denote widebody architectures. Cost savings are on the Y axis, measured in millions of dollars per year based on the operating costs and acquisition cost spread defined in the chapter dealing with creating a baseline model. It can be seen that almost a third of the architectures actually incur more costs in operating the aircraft when compared to today’s baseline,
hence showing negative cost savings. Safety is represented as an adimensional number, computed on the basis of each architecture's ability to deal with a set of safety issues unique to SPO. The value can be anywhere from zero to a hundred, though most architectures fall in the 40 to 75 range, as can be seen. The Utopia point of the tradespace is shown by the green arrow pointing to the upper right corner—a point where safety score and cost savings are at their highest. While the safety score has a maximum possible value of 100 based on the method used to compute it, a theoretical upper limit for cost savings has not been defined. It would be of debatable value, since the calculations are based on assumptions of a notional airline.

Examining the tradespace for non-dominated architectures, it can be seen that a few architectures appear to form a Pareto front. Interestingly, two of the non-dominated architectures involve the concept of a tag-along pilot. A lot of pairing can also be seen amongst the architectures in the tradespace. These
are typically architectures which are similar but differentiated by a weakly sensitive decision like the wingman concept. The architecture closest in distance to the Utopia point is AT(n) – Automation + Tag Along (narrowbody). The architecture with the highest safety scores are VT(n), VT(w) and VT(r) – Virtual pilot + Tag Along. However, this concept generates a negative cost savings of $75m under current assumptions. This is to be expected – the ability of the aircraft to deal with off nominal situations in this architecture is high due to the presence of full auto flight capabilities as well as a backup pilot on board. While the widebody version of this architecture is hugely expensive, the narrowbody and regional jet architectures may well fall within the margin of error for this analysis. Different assumptions for aircraft cost, avionics’ share of aircraft cost, and avionics cost’s relationship with complexity may well see the savings for this concept in the black. Cost savings in other spheres of operation could also bring these concepts into the profitable space. It is also interesting to note how VT(n) and AT(n) are essentially conceptually identical with differences in level of automation, and how this drives a huge cost differential whereas safety score remains in a comparable range. This suggests that more than operational costs, acquisition costs (driven by changes in level of automation) are the factor towards which the architectures are more sensitive.

The architectures with the highest absolute cost savings are AGh(w) and AGhW(w) – Automation + Ground based harbor pilot, and Automation + Ground based harbor pilot + Wingman. This is an example of the aforementioned pairing amongst architectures. Here, both architectures have identical savings but the concept with the wingman has a marginally higher safety score. Both architectures are in the middle of the field in terms of their safety score, which suggests that they may be moved closer to ideal by trading some of the savings for improved safety, and finding additional areas for improvement in cost performance. Of course, the absolute savings number is higher because the cost of operating widebody aircraft are higher, further analysis in terms of relative savings is required for a definitive picture.
Looking only at narrowbody architectures, the earlier point about VT(n) and AT(n) becomes more clear. As can be seen in Figure 17, the safety scores are within 4 points of each other, and operating costs are the same, yet savings are drastically different due to the much higher acquisition costs. The tag along pilot concept had been introduced with the assumption that there would not be much difference in cost savings compared to today's operations since there had to be two fully paid pilots in the flight deck in any case. However, given the fact that it is apparent that acquisition costs driven by the cost of systems on board have a greater sensitivity to the architectural decisions as compared to operating costs, the tag along concept has the greater benefit of eliminating complex and costly systems like autoflight capabilities. Having a second pilot on board means that if the pilot flying fails, the second pilot can take over just like today's operations. The benefits of the tag along concept are amplified in narrowbody operations, since these typically have greater number of departures per day. In today's operations, if a two pilot crew can operate four flights of two hours each, the same crew can operate six flights under
the tag along concept because only one of them is flying at any given time (and assuming the FDTL rule of half of on board rest time being allowed as flying time for the second crew member).

The tag along concept may be seen as a gateway concept to enable widespread SPO. It has the potential to be less disruptive from a perspective of acceptance by the flying community, since two crew members will continue to occupy an aircraft. If we eliminate the tag along concepts from the trade space, then, as the yellow dotted line in Figure 17 depicts, ground pilot based concepts will fall on the pareto front. This indicates that unless there is a radical change in the capabilities of automation, the best replacement for the first officer continues to be a human, whether it is a tag along pilot or a remotely located pilot (albeit the fact that they both perform different functions – the former is a backup, the latter an active participant). Of course, as capabilities of technology improves and the safety score of automation-centric concepts goes up combined with economies of scale kicking in from widespread use of SPO technologies, we can expect many of the architectures to move rightwards and upwards on the tradespace, perhaps supplanting the tag along pilot for a second generation of SPO aircraft.

The narrowbody architecture with the highest savings is AW(n) – Automation + Wingman (narrowbody). However, this also has the second lowest safety scores in the tradespace.
When it comes to widebody aircraft, the picture gets murkier (Figure 18). A greater number of concepts generate negative financial savings compared to narrowbody aircraft. This suggests that fleet and crew utilization may be factors in play that decide the impact of architectural decisions. The safest concept that generates positive savings is AGdW(w) – Automation + Ground based dedicated pilot + Wingman (widebody). The absolute safest widebody concept is VT(w) – Virtual Pilot + Tag along pilot (widebody). The negative savings of $120 million is due to the fact that crews operate fewer flights, and the higher acquisition cost of the Virtual Pilot decision is not balanced by the savings in operating cost like the narrowbodies. Looking at the tradespace, the Pareto front is not entirely clear. The highest absolute savings are made by the concepts involving harbor pilots, though their safety score is considerably lower than concepts with ground based dedicated assistance. In this analysis, one factor not included in ground based dedicated assistance was the number of required ground stations to service a long flight. For narrowbodies, it was assumed that since the average stage length was taken as two hours, the aircraft...
would always be within range of an airport with a ground station. If we imagine a scenario where current airline dispatch centers are converted into ground control stations, almost every major airline has enough ground stations under the narrowbody concept to cover most of North America, as seen in Figure 19. For long haul widebody operations, dedicated support would require ground stations away from home airports and this has not been taken into account. Hence in real life conditions, ground based dedicated assistance will be a somewhat less attractive option for long haul airlines than what the tradespace shows currently.

Harbor pilot concepts have a lower safety score because they are vulnerable in terms of backup capabilities when they are out of range of the harbor pilot. These concepts can be moved to the right with a little investment in auto flight capabilities. In the case of Helios flight 522, even after the pilot was incapacitated, the autopilot kept flying the plane until fuel starvation. Any modern autopilot can be relied on to do the same. If this reliability is improved, and if the auto flight system can be made to hand over the aircraft to the harbor pilot reliably, the safety score should improve considerably. These may
not be high cost changes, when compared to systems like full autonomous flight. The industry has
decades of experience with reliable autopilots that can handle the cruise phase.

The concept with the lowest savings figure is VS(w) – Virtual pilot + Super dispatcher (widebody). While
this may perhaps seem superfluous, or ignoring a likely soft constraint, it is possible to imagine a scenario
where the super dispatcher provides strategic support and the virtual pilot provides tactical support.
However, given the way the virtual pilot was defined in the analysis (as a full auto flight system with
advanced interaction), this high cost was perhaps to be expected.

The most interesting results from the analysis lie in the tradespace for regional aircraft. A majority of the
concepts here appear to lie in the positive savings space of the graph (i.e., above the dotted red line)
and even the ones that incur additional cost have margins that may well lie within the range of error of
this analysis, or may be mitigated through other means. A clearer Pareto front is also visible here, formed by the concepts \(A(r), V(r), AT(r),\) and \(VT(r)\). \(A(r)\) and \(V(r)\), which are concepts with automation only as the assistance for the human pilot, appear to have the greatest cost savings while possessing a lower safety score. Adding a tag along pilot to these architectures takes them well to the right of the graph on safety. The ideal architecture seems to be \(AT(r)\), which is the closest to the Utopia point with a safety score of 71.3 and an annual savings of $95 million on the notional fleet.

The only two concepts that generate additional costs are \(VS(r)\) and \(VT(r)\). Of these, the former, which has a lower safety score and higher cost incurred, can be rejected. The latter, which involved a virtual pilot and a tag along pilot, has the highest safety score and generates an additional cost of only $9 million annually for the notional fleet, which may well be mitigated by savings in other components of acquisition cost. Overall, it appears from the tradespace that every architecture for regional aircraft may be implementable, so long as means are found to increase safety without eroding the cost advantage too much. It must also be noted that since these aircraft often fly shorter routes and are in greater proximity to airports, some of the safety assumptions used for the analysis may not affect them to the same extent as on narrowbodies and widebodies, which may move the safety scores to the right without incurring higher costs. In summation, it should not come as a surprise that Embraer, a manufacturer of regional jets, chose to be the first to announce SPO capable aircraft, since the biggest promise for savings in SPO appears to lie in the regional aircraft space.
7. CONCLUSIONS

In Chapter 3 when dealing with the viability of single pilot operations, two key questions were posed:

- Can commercial air transport operations be conducted with a single pilot operating the aircraft?
- Is it desirable to operate commercial transport aircraft with only a single pilot?

To conclude this study, it would be a good idea to revisit these questions, and to try and answer them again in light of insights from the analysis performed so far. The first question, as stated earlier, deals with the safety aspect of SPO. The answer to the first question can be best summed up as, it depends. Safe SPO operations are dependent on the architectural choices made in enabling SPO. The analysis reveals that the architectural concepts proposed in the literature review so far have differing levels of ability to deal with safety concerns. Pilot incapacitation is mentioned as a major concern. Architectures that replace the F/O with automation will need to develop capabilities to detect and react to pilot incapacitation scenarios. Architectures that carry an extra non-functioning pilot on board currently appear to be the most cost effective means to neutralize pilot incapacitation. This can be seen in the tradespace analysis where these architectures perform better than expected in terms of cost savings versus safety.

A key revelation from the pilot workload portion of the study is that no architecture scores anywhere close to the current baseline in terms of managing the workload shifting to the pilot flying. While the method employed has its limitations – it compares changes in total possible pilot actions across different phases, actual pilot engagement varies based on a given flight scenario – it is important to note that even in architectures where a human replaces the F/O on the ground, the workload on the pilot flying goes up. The reason for this is that some decisions must remain ‘in the air’. For instance, fuel management can be performed by the pilot flying with the help of automation, or by the automation with the supervision of the pilot flying. It would be unwise for instance to hand fuel management to a person on the ground, and cut the pilot flying out of the loop. In the current scenario, the pilot
monitoring would perform these duties, and regardless of the level of automation assistance, keeps this process off the pilot flying’s plate. Similar other processes all add up and move some responsibility to the pilot flying, regardless of architecture. While increasing automation for such processes is an obvious answer, it should be compared against increases in subsystem cost in a more detailed study (this analysis treats all subsystems as if they were of equal complexity).

In terms of off-nominal situations, architectures with tag along pilots on board perform as well as today’s operations, because they have an extra human resource on board in any emergency. The problem with all other architectures which have only one pilot on board is that under today’s scenario, due to the complex nature of aircraft systems there are failure combinations that can generate a large number of ECAM messages and checklist actions. Qantas 32, for instance, had 43 ECAM messages to deal with, in addition to numerous checklists to be dealt with. While modern aircraft systems can process these into a single prioritized list of actions, the actual ability of a single pilot to deal with complex emergencies will depend a great deal on the design of automated checklist systems in the future. Having a human F/O on board has a distinct advantage in that the pilot flying can handle the aircraft and radios, while the F/O goes about performing checklist actions. It is likely that there would be a significant number of checklist actions that must be performed by a human, and not automation, so it is reasonable to expect that automated checklist systems will be somewhat limited in this regard. What will be key is to enable the pilot to perform remaining checklist actions without losing sight of his primary goal of flying the plane, even when he has to resort to flying it manually. This enablement can happen through more efficient human machine interaction, through the use of voice, advanced HUDs, and multi-modal interfaces. It is useful to remember that the military have been flying advanced single pilot aircraft for decades (albeit with lower requirements of reliability and redundancy than civil air transport) and useful technologies and procedures may be adopted from their best practices. For instance, head-mounted displays may hold promise in mitigating the problem of having one pilot cycling between head-up time and head-down time. Devices similar to what military pilots wear (but far less obtrusive) could become part of civil air transport as well – gloves monitoring vital statistics and keeping oxygen masks on all the time are potential examples. To sum up, SPO architectures could conceivably handle off-nominal situations without many issues, but the technology comes with a price.
The second question deals with the financial implications of moving to SPO. While this study started out by citing labour costs as one of the motivators for moving to SPO, the analysis reveals that some of the technology changes required in the process are quite expensive, and would add significantly to the ownership costs of a new SPO airplane. The analysis took into account the fact that there is typically an increase in price associated with the introduction of a new generation of aircraft, but even taking that into account, SPO pushed costs higher in many architectures. Some architectures with lower cost implications stayed within the bracket of the expected increase, but the most capable and safe architectures were too expensive compared to today's costs. The analysis does have its limitations in that notional values were assumed for aircraft and that the total acquisition cost was spread across an assumed 20 year lifespan without taking into account depreciation and other externalities.

The cost of avionics as a share of the total airframe cost has been increasing, with more and more capabilities being added to the systems on board. At list price without taking into account discounts, a 400 million dollar A380 costs the same as paying 100 pilots $250k for 16 years, which is shorter than what most operators intend to keep that aircraft for. So it is conceivable that bigger savings are to be made in keeping the airframe costs low. Architectures that save on capability addition by continuing to use a second human either located remotely or on board as a backup are the ones most promising from a financial standpoint. However, these architectures are more efficient only in the context of short haul narrowbody operations, as can be seen from the tradespace analysis.

Perhaps the most important finding of this analysis is the influence of operational context on architectural choices. The tag along pilot concept is a good example of this. In a short haul, high utilization, LCC type scenario, the concept extends total crew productivity and, combined with simpler cheaper on board systems, provides excellent cost savings. This architecture also emerges as a clear frontrunner in the analysis conducted for regional aircraft. In a long haul scenario, where the departures per day are fewer, and crew operate far fewer albeit longer flights – the average flight is often longer than a pilot’s FDTL time – the concept becomes far less effective because it now makes only augmented crew flights more productive, and those constitute a very low percentage of total flights under SPO. In fact, widebody long haul operations requires further study with more accurate cost data, since the margins of error may be distorting the tradespace for these architectures.
7.1 Areas for Further Study

SPO is a vast and complex subject that would require a lot of effort by academia and industry before it comes to fruition. As mentioned in the literature review, there is some effort underway towards answering the questions posed by this challenging set of concepts, but it is far from the level of focus that is required. As can be seen in the analysis performed in this thesis, operating context is an important factor in choosing SPO architectures. As such, one of the most evident areas for future focus is the business impact of SPO. The benefits and shortcomings of SPO for various types of operators – passenger airlines, cargo operators, regional airlines, special mission operators – needs to be identified. As aircraft are increasingly designed with versatile roles in mind, it becomes important to identify potential for architectural commonality and modularity that would possibly address the needs of all these different types of operators. While resources such as the MIT Airline Data Project have a wealth of data that would prove to be a good starting point for such a study, it is important to engage real world stakeholders from the industry to better understand their insights as the potential end user, especially qualitative ones.

A second and critical area of focus is the study of pilot workload in SPO, especially under off-nominal conditions. While this analysis attempted to quantify workload and off-nominal performance to an extent, the overall focus of the study was architectural comparison, and as such does not go anywhere near the fidelity required in the identification of pilot workload. As mentioned in the literature review, regulatory authorities have rightly placed the burden on manufacturers and operators in the past when reduced crew operations were mooted, and the ability of a single pilot aircraft to prove that its pilot undergoes a level of workload equal to or less that what an individual crew member would face in today’s two pilot flight decks would be the litmus test for gaining regulatory approval. As such, there is a need for human performance models to be used to identify the level of workload in SPO architectures, and to find solutions that bring it to acceptable levels.

While this thesis had a defined scope of high level architectural comparisons for SPO, future work may need to focus one or two levels down with subsystems and their capabilities modeled in greater detail. This would require accurate data for cost and performance, and fewer assumptions, such that it would be possible to generate architectural combinations with greater detail and fidelity when compared to
actual aircraft systems. The definition of the systems with greater detail would allow us to better define
the precise capabilities of the architecture, and better predict its ability to deal with off nominal
situations and corner cases.

Pilot incapacitation is mentioned many times in the literature that was reviewed as part of this thesis,
however, there are very few studies that attempt to find ways to deal with this situation. Clearly there
is no such incentive for such a study today because there is a second crew member present, but for the
move to SPO, such a study becomes critical. An SPO focused pilot incapacitation study must focus not
only on the means to negate the effects of incapacitation on flight operations, but also focus on
prevention. This would include the study of diseases and their geographical distribution amongst the
world’s pilot population, so as to better attune local efforts at ground based preventive screenings. Pilot
incapacitation studies also need to focus on mental health, and looking at means to prevent deliberate
pilot action detrimental to the fate of the aircraft and its occupants.

Research is also required into moral and ethical questions around SPO. Similar to autonomous cars
having to deal with scenarios where the vehicle has to choose between saving one and three lives, SPO
aircraft must be seen as a system that can be controlled by a human in the air, the on board systems, a
human on the ground, and systems on the ground. The degree and hierarchy of control, as well as
permissions for actions, needs to be carefully thought out, especially since there are scenarios where a
person who is not on board the aircraft, and hence has ‘no skin in the game’, is placed in charge of the
lives of scores of people far away from them.

A final, and personal, question also remains to be answered. As someone who is a keen pilot, it is
obviously a bit amusing to have worked on a thesis that aims to cut the required pilot population by up
to a half. Pilot shortages have been forecast for a while now by the airline industry, and the combination
of extremely expensive initial training and extremely low entry level remuneration has led to fewer
people – myself included – choosing flying as a profession. SPO has the potential to both soothe and
exacerbate this problem, and industry bodies studying pilot shortage in the long term should also work
to examine the effect of SPO on the flight training market.
8. APPENDIX

8.1 Architecture A – Methods and Scores

Levels of Automation

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<td>1 Crew arrives</td>
<td>Scheduling</td>
<td></td>
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<tr>
<td>2 Dispatch</td>
<td>Dispatcher</td>
<td>Review/accept</td>
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<tr>
<td>3 Crew meeting</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 Transfer to aircraft</td>
<td></td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>5 Arrive at airport</td>
<td>Gate staff</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 Aircraft status/Status of process Aircraft ready - technical register of airplane</td>
<td>Maintenance, Ramp</td>
<td>Safety check</td>
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</tr>
<tr>
<td>7 Full crew briefing</td>
<td>Cabin Crew</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 Cabin ready to board</td>
<td>Cabin Crew</td>
<td>Coord prep, checklists</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9 All doors closed</td>
<td>Cabin Crew</td>
<td>48</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 Out of gate/off blocks</td>
<td>ATC Ramp</td>
<td>Engine start CL (15)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11 Taxi</td>
<td>ATC Ground</td>
<td>Pre-departure CL (17)</td>
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<td></td>
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<tr>
<td>12 Ready for takeoff</td>
<td>ATC Tower</td>
<td>Before TO CL (7); Callouts, TO decision</td>
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<td>13 Climb</td>
<td>ATC Departure</td>
<td>After takeoff CL (8)</td>
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<tr>
<td>14 Cruise</td>
<td>ATC Enroute</td>
<td>Automation interactions</td>
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<tr>
<td>15 Before top of descent</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16 Top of descent</td>
<td>15 minutes before landing</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17 1000ft/3-4 miles before landing</td>
<td>ATC Approach</td>
<td>Before landing CL (16)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18 At transition level</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19 Initial approach fix</td>
<td></td>
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<td></td>
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<tr>
<td>20 Final approach fix</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21 Decision height</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22 1000 ft / 3-4 miles before landing</td>
<td>ATC Tower</td>
<td>Autoland decision</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23 Decision height</td>
<td>Callouts</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24 Landing and rollout</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25 Taxi</td>
<td>ATC Ground</td>
<td>After landing CL (8)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>26 Park and shutdown</td>
<td>ATC Ramp</td>
<td>Parking CL (7);, securing aircraft CL (9)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>27 Flight report</td>
<td>Maintenance</td>
<td>Safety, Maintenance report decision</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>28 Change aircraft/prepares for next flight</td>
<td>Scheduling</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* - numbers in brackets ( ) indicate number of checklist items, based on A320 normal operations checklist. CL stands for checklist. Some checklists have been combined for better alignment with process gates in this model.

Off-Nominals

<table>
<thead>
<tr>
<th>Off Nominals</th>
<th>#CL Actions</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dual Engine Fail + Ditching</td>
<td>41</td>
<td>2</td>
</tr>
<tr>
<td>Avionics Smoke + Emer. Descent</td>
<td>36</td>
<td>3.5</td>
</tr>
<tr>
<td>High engine vibration + abnormal lgd gear</td>
<td>36</td>
<td>5.5</td>
</tr>
<tr>
<td>Pilot incapacitation</td>
<td>incap + recover</td>
<td>10</td>
</tr>
</tbody>
</table>

New Systems

<table>
<thead>
<tr>
<th>New systems / capabilities</th>
<th>Cost Inc. %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auto checklists</td>
<td>2</td>
</tr>
<tr>
<td>Speech recognition</td>
<td>4</td>
</tr>
<tr>
<td>Incapacitation check system</td>
<td>4</td>
</tr>
<tr>
<td>Digital Parachute</td>
<td>10</td>
</tr>
</tbody>
</table>
### Costs

#### Operating Costs

| Fleet size | 300 |
| Fleet type | NB  |
| Pilot group| 3600|
| Average Pay | $150,000.00 per annum |
| Wage Bill | $540,000,000.00 per annum |
| Departures per day | 5 per aircraft |
| Total flights per day | 1500 |
| Avg stage time | 2 hours |
| Flights per pilot per day | 4 assumed same FDTL |
| Daily pilot requirement | 375 |
| Total pilot group requirement | 1800 |
| New wage bill | $270,043,207 per annum |
| Annual wage savings | $269,956,793 per annum |
| Savings % | 49.99% |

#### Acquisition Costs

| Base.Line Cost | $100,000,000 |
| Avionics Cost | $25,000,000 |

| Total step change in LoA | 18.5 |
| LoA based cost change % | 46.25 |
| Cost change value | $11,562,500 |
| New systems | 4 |
| New systems cost change % | 20 |
| Cost change value | $5,000,000 |

| Total cost change | $16,562,500 |
| New Avionics Cost | $41,562,500 |
| New Baseline Cost | $116,562,500 |
| 20 yr annual spread | $5,828,125 |
| Annual increase fleetwide | $248,437,500 |
| Increase attributable to SPO | $98,437,500 |

| Baseline Cost | $200,000,000 |
| Avionics Cost | $50,000,000 |

| Total step change in LoA | 18.5 |
| LoA based cost change % | 46.25 |
| Cost change value | $23,125,000 |
| New systems | 4 |
| New systems cost change % | 20 |
| Cost change value | $10,000,000 |

| Total cost change | $33,125,000 |
| New Avionics Cost | $83,125,000 |
| New Baseline Cost | $233,125,000 |
| 20 yr annual spread | $11,656,250 |
| Annual increase fleetwide | $496,875,000 |
| Increase attributable to SPO | $2,671,875,000 |

| Baseline Cost | $50,000,000 |
| Avionics Cost | $12,500,000 |

| Total step change in LoA | 18.5 |
| LoA based cost change % | 46.25 |
| Cost change value | $5,781,250 |
| New systems | 4 |
| New systems cost change % | 20 |
| Cost change value | $2,500,000 |

| Total cost change | $8,281,250 |
| New Avionics Cost | $20,781,250 |
| New Baseline Cost | $58,281,250 |
| 20 yr annual spread | $2,914,063 |
| Annual increase fleetwide | $124,218,750 |
| Increase attributable to SPO | $49,218,750 |
8.1.3 Workload Score

Baseline PF
Workload %
0.17 0.22 0.25

New PF Wload %
0.52 0.46 0.50

Wload Score
6.5 4.8 10.0 21.3 Total
8.2 Architecture AGd – Methods and Scores

Levels of Automation

<table>
<thead>
<tr>
<th>Process Gate</th>
<th>Flight Crew Communication</th>
<th>Flight Crew Deacisions &amp; Actions*</th>
<th>Captain Systems Interaction</th>
<th>Automation</th>
<th>Ground Based Dedicated Pilot</th>
<th>Level of Automation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Crew arrives</td>
<td>Scheduling</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>MC</td>
</tr>
<tr>
<td>2 Dispatch</td>
<td>Dispatcher</td>
<td>Review/accept</td>
<td>Desktop s/w, wx, flt plan, wt &amp; tel</td>
<td></td>
<td></td>
<td>AS</td>
</tr>
<tr>
<td>3 Crew meeting</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 Transfer to aircraft</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 Arrive at aircraft</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 Aircraft status/status of aircraft</td>
<td></td>
<td>Maintenance, technical register of airplane</td>
<td></td>
<td></td>
<td></td>
<td>MC</td>
</tr>
<tr>
<td>7 Full crew briefing</td>
<td>Captain Crew</td>
<td>Cockpit prep, checklists</td>
<td>Electric, APU, Hydraulics, FMC (Air data, Nav, FPL), Cabin environment, ECAM</td>
<td>Cl Support, Data Comm (clearance)</td>
<td>Monitor</td>
<td>AS</td>
</tr>
<tr>
<td>8 Cabin ready to board</td>
<td>Captain Crew</td>
<td></td>
<td>Electric, APU, Hydraulics, FMC (Air data, Nav, FPL), Cabin environment, ECAM</td>
<td>Cl Support, Data Comm, Monitor</td>
<td>Monitor</td>
<td>AS</td>
</tr>
<tr>
<td>9 All doors closed</td>
<td>Captain Crew</td>
<td></td>
<td>Electric, APU, Hydraulics, FMC (Air data, Nav, FPL), Cabin environment, ECAM</td>
<td>Cl Support, Data Comm, Monitor</td>
<td>Monitor</td>
<td>AS</td>
</tr>
<tr>
<td>10 Out of gate/off blocks</td>
<td>ATC Ramp</td>
<td>Engine start</td>
<td>Electric, APU, Hydraulics, FMC (Air data, Nav, FPL), Cabin environment, ECAM</td>
<td>Cl Support, Data Comm, Monitor</td>
<td>Monitor</td>
<td>AS</td>
</tr>
<tr>
<td>11 Taxi</td>
<td>ATC Ground</td>
<td>Pre-departure</td>
<td>Electric, APU, Hydraulics, FMC (Air data, Nav, FPL), Cabin environment, ECAM</td>
<td>Cl Support, Data Comm, Monitor</td>
<td>Monitor</td>
<td>AS</td>
</tr>
<tr>
<td>12 Ready for takeoff</td>
<td>ATC Tower</td>
<td>Take-off</td>
<td>Electric, APU, Hydraulics, FMC (Air data, Nav, FPL), Cabin environment, ECAM</td>
<td>Cl Support, Data Comm, Monitor</td>
<td>Monitor</td>
<td>AS</td>
</tr>
<tr>
<td>13 Check</td>
<td>ATC Departure</td>
<td>After takeoff</td>
<td>Electric, APU, Hydraulics, FMC (Air data, Nav, FPL), Cabin environment, ECAM</td>
<td>Cl Support, Data Comm, Monitor</td>
<td>Monitor</td>
<td>AS</td>
</tr>
<tr>
<td>14 Cruise</td>
<td>ATC Enroute</td>
<td>Automation</td>
<td>Electric, APU, Hydraulics, FMC (Air data, Nav, FPL), Cabin environment, ECAM</td>
<td>Cl Support, Data Comm, Monitor</td>
<td>Monitor</td>
<td>AS</td>
</tr>
<tr>
<td>15 Before top of descent</td>
<td>ATC Approach</td>
<td>Before landing</td>
<td>Electric, APU, Hydraulics, FMC (Air data, Nav, FPL), Cabin environment, ECAM</td>
<td>Cl Support, Data Comm, Monitor</td>
<td>Monitor</td>
<td>AS</td>
</tr>
<tr>
<td>16 Top of descent</td>
<td>ATC Approach</td>
<td>After landing</td>
<td>Electric, APU, Hydraulics, FMC (Air data, Nav, FPL), Cabin environment, ECAM</td>
<td>Cl Support, Data Comm, Monitor</td>
<td>Monitor</td>
<td>AS</td>
</tr>
<tr>
<td>17 35 minutes before landing</td>
<td>ATC Approach</td>
<td></td>
<td>Electric, APU, Hydraulics, FMC (Air data, Nav, FPL), Cabin environment, ECAM</td>
<td>Cl Support, Data Comm, Monitor</td>
<td>Monitor</td>
<td>AS</td>
</tr>
<tr>
<td>18 3000 ft/5 miles before landing</td>
<td>ATC Approach</td>
<td></td>
<td>Electric, APU, Hydraulics, FMC (Air data, Nav, FPL), Cabin environment, ECAM</td>
<td>Cl Support, Data Comm, Monitor</td>
<td>Monitor</td>
<td>AS</td>
</tr>
<tr>
<td>19 Transition level</td>
<td>ATC Approach</td>
<td>Before landing</td>
<td>Electric, APU, Hydraulics, FMC (Air data, Nav, FPL), Cabin environment, ECAM</td>
<td>Cl Support, Data Comm, Monitor</td>
<td>Monitor</td>
<td>AS</td>
</tr>
<tr>
<td>20 Initiate approach fix</td>
<td>ATC Approach</td>
<td></td>
<td>Electric, APU, Hydraulics, FMC (Air data, Nav, FPL), Cabin environment, ECAM</td>
<td>Cl Support, Data Comm, Monitor</td>
<td>Monitor</td>
<td>AS</td>
</tr>
<tr>
<td>21 Final approach fix</td>
<td>ATC Approach</td>
<td></td>
<td>Electric, APU, Hydraulics, FMC (Air data, Nav, FPL), Cabin environment, ECAM</td>
<td>Cl Support, Data Comm, Monitor</td>
<td>Monitor</td>
<td>AS</td>
</tr>
<tr>
<td>22 3 000 ft 3-4 miles before landing</td>
<td>ATC Approach</td>
<td></td>
<td>Electric, APU, Hydraulics, FMC (Air data, Nav, FPL), Cabin environment, ECAM</td>
<td>Cl Support, Data Comm, Monitor</td>
<td>Monitor</td>
<td>AS</td>
</tr>
<tr>
<td>23 Decision height</td>
<td>ATC Tower</td>
<td></td>
<td>Electric, APU, Hydraulics, FMC (Air data, Nav, FPL), Cabin environment, ECAM</td>
<td>Cl Support, Data Comm, Monitor</td>
<td>Monitor</td>
<td>AS</td>
</tr>
<tr>
<td>24 Landing and rollout</td>
<td>ATC Approach</td>
<td>After landing</td>
<td>Electric, APU, Hydraulics, FMC (Air data, Nav, FPL), Cabin environment, ECAM</td>
<td>Cl Support, Data Comm, Monitor</td>
<td>Monitor</td>
<td>AS</td>
</tr>
<tr>
<td>25 Taxi</td>
<td>ATC Ground</td>
<td></td>
<td>Electric, APU, Hydraulics, FMC (Air data, Nav, FPL), Cabin environment, ECAM</td>
<td>Cl Support, Data Comm, Monitor</td>
<td>Monitor</td>
<td>AS</td>
</tr>
<tr>
<td>26 Park and shutdown</td>
<td>ATC Ramp</td>
<td></td>
<td>Electric, APU, Hydraulics, FMC (Air data, Nav, FPL), Cabin environment, ECAM</td>
<td>Cl Support, Data Comm, Monitor</td>
<td>Monitor</td>
<td>AS</td>
</tr>
<tr>
<td>27 Flight report</td>
<td>Maintenance</td>
<td>Safety, maintenance report decision</td>
<td>Electric, APU, Hydraulics, FMC (Air data, Nav, FPL), Cabin environment, ECAM</td>
<td>Cl Support, Data Comm, Monitor</td>
<td>Monitor</td>
<td>AS</td>
</tr>
<tr>
<td>28 Change aircraft/prepare for next flight</td>
<td>Scheduling</td>
<td></td>
<td>Electric, APU, Hydraulics, FMC (Air data, Nav, FPL), Cabin environment, ECAM</td>
<td>Cl Support, Data Comm, Monitor</td>
<td>Monitor</td>
<td>AS</td>
</tr>
</tbody>
</table>

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Off-Nominals

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<th>Off Nominals</th>
<th>#CL Actions</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dual Engine Fail + Ditching</td>
<td>41</td>
<td>3</td>
</tr>
<tr>
<td>Avionics Smoke + Emer. Descent</td>
<td>36</td>
<td>5</td>
</tr>
<tr>
<td>High engine vibration + abnormal lgd gear</td>
<td>36</td>
<td>6</td>
</tr>
<tr>
<td>Pilot incapacitation</td>
<td>Human on the gnd</td>
<td>can fly</td>
</tr>
</tbody>
</table>

New Systems

<table>
<thead>
<tr>
<th>New systems / capabilities</th>
<th>Cost inc. %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speech recognition</td>
<td>4</td>
</tr>
<tr>
<td>Incapacitation check system</td>
<td>4</td>
</tr>
<tr>
<td>Remote controlled flight</td>
<td>7</td>
</tr>
<tr>
<td>9 for wb</td>
<td></td>
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</table>
## Costs

### Operating Costs

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fleet size</td>
<td>300</td>
</tr>
<tr>
<td>Fleet type</td>
<td>NB</td>
</tr>
<tr>
<td>Pilot group</td>
<td>3600</td>
</tr>
<tr>
<td>Average Pay</td>
<td>$150,000.00</td>
</tr>
<tr>
<td>Wage Bill</td>
<td>$540,000,000.00</td>
</tr>
<tr>
<td>Average ground pilot pay</td>
<td>$140,000.00 per annum, flight duty diff</td>
</tr>
<tr>
<td>Departures per day</td>
<td>5 per aircraft</td>
</tr>
<tr>
<td>Total flights</td>
<td>1500</td>
</tr>
<tr>
<td>Avg stage time</td>
<td>2 hours</td>
</tr>
<tr>
<td>Flights per pilot per day</td>
<td>4 assumed same FDTL</td>
</tr>
<tr>
<td>Flights per gnd pilot per day</td>
<td>4 assumed same FDTL</td>
</tr>
<tr>
<td>Daily pilot requirement</td>
<td>375</td>
</tr>
<tr>
<td>Daily gnd pilot requirement</td>
<td>375</td>
</tr>
<tr>
<td>Total pilot group requirement</td>
<td>3601 gnd + air even split</td>
</tr>
<tr>
<td>New wage bill</td>
<td>$522,140,000 per annum</td>
</tr>
<tr>
<td>Annual wage savings</td>
<td>$17,860,000 per annum</td>
</tr>
<tr>
<td>Savings %</td>
<td>3.31% per annum</td>
</tr>
<tr>
<td>Fleet size</td>
<td>300</td>
</tr>
<tr>
<td>Fleet type</td>
<td>WB</td>
</tr>
<tr>
<td>Pilot group</td>
<td>3000</td>
</tr>
<tr>
<td>Average Pay</td>
<td>$190,000.00 per annum</td>
</tr>
<tr>
<td>Wage Bill</td>
<td>$570,000,000.00 per annum</td>
</tr>
<tr>
<td>Average ground pilot pay</td>
<td>$175,000.00 per annum</td>
</tr>
<tr>
<td>Departures per day</td>
<td>1.5</td>
</tr>
<tr>
<td>Total flights</td>
<td>450</td>
</tr>
<tr>
<td>Avg stage time</td>
<td>9 hours</td>
</tr>
<tr>
<td>Flights per pilot per day</td>
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</tr>
<tr>
<td>Flights per gnd pilot per day</td>
<td>1</td>
</tr>
<tr>
<td>Daily pilot requirement</td>
<td>563 augmentation included</td>
</tr>
<tr>
<td>Daily gnd pilot requirement</td>
<td>563</td>
</tr>
<tr>
<td>Total pilot group requirement</td>
<td>3001</td>
</tr>
<tr>
<td>New wage bill</td>
<td>$547,675,000 per annum</td>
</tr>
<tr>
<td>Annual wage savings</td>
<td>$22,325,000 per annum</td>
</tr>
<tr>
<td>Savings %</td>
<td>3.92% per annum</td>
</tr>
</tbody>
</table>

### Acquisition Costs

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline Cost</td>
<td>$100,000,000</td>
</tr>
<tr>
<td>Avionics Cost</td>
<td>$25,000,000</td>
</tr>
<tr>
<td>Total step change in LoA</td>
<td>9</td>
</tr>
<tr>
<td>LoA based cost change %</td>
<td>22.50</td>
</tr>
<tr>
<td>Cost change value</td>
<td>$5,625,000</td>
</tr>
<tr>
<td>New systems</td>
<td>3</td>
</tr>
<tr>
<td>New systems cost change %</td>
<td>15</td>
</tr>
<tr>
<td>Cost change value</td>
<td>$3,750,000</td>
</tr>
<tr>
<td>New Avionics Cost</td>
<td>$34,375,000</td>
</tr>
<tr>
<td>New Baseline Cost</td>
<td>$109,375,000</td>
</tr>
<tr>
<td>20 yr annual spread</td>
<td>$5,468,750</td>
</tr>
<tr>
<td>Annual increase fleetwide</td>
<td>$140,625,000</td>
</tr>
<tr>
<td>Increase attributable to SPO</td>
<td>-$3,750,000</td>
</tr>
<tr>
<td>Baseline Cost</td>
<td>$200,000,000</td>
</tr>
<tr>
<td>Avionics Cost</td>
<td>$50,000,000</td>
</tr>
<tr>
<td>Total step change in LoA</td>
<td>9</td>
</tr>
<tr>
<td>LoA based cost change %</td>
<td>22.50</td>
</tr>
<tr>
<td>Cost change value</td>
<td>$11,250,000</td>
</tr>
<tr>
<td>New systems</td>
<td>3</td>
</tr>
<tr>
<td>New systems cost change %</td>
<td>17</td>
</tr>
<tr>
<td>Cost change value</td>
<td>$8,500,000</td>
</tr>
<tr>
<td>New Avionics Cost</td>
<td>$68,750,000</td>
</tr>
<tr>
<td>New Baseline Cost</td>
<td>$219,750,000</td>
</tr>
<tr>
<td>20 yr annual spread</td>
<td>$10,987,500</td>
</tr>
<tr>
<td>Annual increase fleetwide</td>
<td>$296,250,000</td>
</tr>
<tr>
<td>Increase attributable to SPO</td>
<td>-$3,750,000</td>
</tr>
<tr>
<td>Baseline Cost</td>
<td>$50,000,000</td>
</tr>
<tr>
<td>Avionics Cost</td>
<td>$12,500,000</td>
</tr>
<tr>
<td>Total step change in LoA</td>
<td>9</td>
</tr>
<tr>
<td>LoA based cost change %</td>
<td>22.50</td>
</tr>
<tr>
<td>Cost change value</td>
<td>$2,812,500</td>
</tr>
<tr>
<td>New systems</td>
<td>3</td>
</tr>
<tr>
<td>New systems cost change %</td>
<td>15</td>
</tr>
<tr>
<td>Cost change value</td>
<td>$1,875,000</td>
</tr>
<tr>
<td>New Avionics Cost</td>
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## 8.3 Architecture AS – Methods and Scores

### Levels of Automation

<table>
<thead>
<tr>
<th>Process Gate</th>
<th>Right Crew Communication</th>
<th>Right Crew Decisions &amp; Actions*</th>
<th>Captain Systems Interaction</th>
<th>Automation</th>
<th>Super Dispatcher</th>
<th>Level of Automation</th>
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<tbody>
<tr>
<td>1. Crew arrives</td>
<td>Scheduling</td>
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<td>2. Dispatch</td>
<td>Dispatcher</td>
<td>Review/accept</td>
<td>Desktop UI, ws, fitness, wt &amp; bald</td>
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<td>3. Crew meeting</td>
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<td>4. Transfer to aircraft</td>
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<td>5. Arrive at aircraft</td>
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<td>6. Ready - technical register of airplane</td>
<td>Maintenance, Ramp</td>
<td>Safety check</td>
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<tr>
<td>7. Full new briefing</td>
<td>Cabin Crew</td>
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<td>8. Cabin ready to board</td>
<td>Cabin Crew</td>
<td>Cabin Prep, checklists (46)</td>
<td>Electrics, APU, hydraulic, FMC (air data, nav, fuel), cabin environment, ECAM (Fuel, doors, flight controls, Xps, Comm's (radio, intercom))</td>
<td>Automated C support</td>
<td>Monitor, blinl comm's (bliner)</td>
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<td>9. All doors closed</td>
<td>Cabin Crew</td>
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<td>Electrics, APU, ECAM (fuel, doors), doors, radio comms,</td>
<td>Automated C support for cap't systems, Monitor Systems</td>
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<td>SHC 2</td>
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<tr>
<td>10. Out of gate/flight blocks</td>
<td>ATC Ramp</td>
<td>Engine start CL (15)</td>
<td>Electric, Hydraulic, Brakes, ECAM, APU,</td>
<td>Automated C support for flight systems</td>
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<tr>
<td>11. Taxi</td>
<td>ATC Ground</td>
<td>Pre-departure CL (13)</td>
<td>Electric, Hydraulic, Brakes, ECAM, APU,</td>
<td>Automated C support for flight systems</td>
<td>Monitor</td>
<td>RS 5</td>
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<tr>
<td>12. Ready for takeoff</td>
<td>ATC Tower</td>
<td>Before TC/CL (10), Cellulose, 10 decision</td>
<td>Electric, Hydraulic, Brakes, Electric, Engines, Radi (TCAS),</td>
<td>Automated C support for cap't systems</td>
<td>Monitor</td>
<td>BDM 4</td>
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<tr>
<td>13. Climb</td>
<td>ATC Departure</td>
<td>After takeoff CL (9)</td>
<td>Electric, Hydraulic, Electric, Radio comms</td>
<td>Automated C support for cap't systems</td>
<td>Monitor</td>
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<tr>
<td>14. Cruise</td>
<td>ATC Enroute</td>
<td>Automation programming</td>
<td>Electric, Nav, FMC cross check, Radio comms,</td>
<td>Automated C support for cap't systems</td>
<td>Monitor</td>
<td>SC 0</td>
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<td>15. Before top of descent</td>
<td>ATC Approach</td>
<td>Before landing CL (10)</td>
<td>Electric, Hydraulic, Radio comms</td>
<td>Automated C support, SOP actions, In incapacitation check</td>
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<td>16. Top of descent</td>
<td>ATC Approach</td>
<td>Before landing CL (10)</td>
<td>Electric, Hydraulic, Radio comms</td>
<td>Automated C support, SOP actions, In incapacitation check</td>
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<td>17. 10 minutes before landing</td>
<td>ATC Tower</td>
<td>Autoland decision</td>
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<td>18. 10000 ft/aircraft cockpit</td>
<td>ATC Tower</td>
<td>Cellulose</td>
<td>Electric, APU, Electric, Radio comms, Automated C support, SOP actions</td>
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<td>19. At transition level</td>
<td>ATC Ground</td>
<td>After landing CL (10)</td>
<td>Electric, Hydraulic, Engines, Xpl, Electric, Radio comms</td>
<td>Automated C support, SOP actions</td>
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<td>20. Initial approach fix</td>
<td>ATC Tower</td>
<td>Autoland decision</td>
<td>Electric, Xpl, Electric, Electric, Radio comms, Automated C support, SOP actions</td>
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<td>21. Final approach fix</td>
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<td>22. 500/3/4 miles before landing</td>
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<td>23. Decision height</td>
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<td>FMC (Alt), Electric, Radio comms, Automated C support, SOP actions</td>
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<td>24. Landing and rollout</td>
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<td>Decision support</td>
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<td>25. Taxi</td>
<td>ATC Ground</td>
<td>After landing CL (10)</td>
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<td>Automated C support, SOP actions</td>
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<td>SHC 2</td>
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<tr>
<td>27. Flight report</td>
<td>Maintenance</td>
<td>Safety, Maintenance report device</td>
<td>Electric, Xpl, Electric, Electric, Radio comms, Automated C support, SOP actions</td>
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<tr>
<td>28. Change aircraft/prepare for next flight</td>
<td>Scheduling</td>
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<td>BDM on autoland, DL otherwise 1</td>
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* Numbers in brackets ( ) indicate number of checklist items, based on A320 normal operations checklist. CL stands for checklist. Some checklists have been combined for better alignment with process gates in this model.

### Off-Nominals

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<td>Dual Engine Fail + Ditching</td>
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<tr>
<td>Avionics Smoke + Emer. Descent</td>
<td>36</td>
<td>4</td>
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<tr>
<td>High engine vibration + abnormal lgd gear</td>
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### New Systems

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<td>Incapacitation check system</td>
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<tr>
<td>Advanced Datalink</td>
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<tr>
<td>Digital Parachute</td>
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<tr>
<td>Costs</td>
<td>Acquisition Costs</td>
</tr>
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<td>-------------------------------------------------------</td>
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<td><strong>Baseline Cost</strong></td>
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<tr>
<td>Fleet size</td>
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<tr>
<td>Fleet type</td>
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<tr>
<td>Pilot group</td>
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</tr>
<tr>
<td>Average Pay</td>
<td>$150,000,000 per annum</td>
</tr>
<tr>
<td>Wage Bill</td>
<td>$540,000,000 per annum</td>
</tr>
<tr>
<td>Average Super Dispatcher pay</td>
<td>$150,000,000 per annum, flight duty diff</td>
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<td>Total flights</td>
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<td>Avg stage time</td>
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<tr>
<td>Flights per pilot per day</td>
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</tr>
<tr>
<td>Flights per super dispatcher per day</td>
<td>20 per annum, assumed same FDL, 5 concurrent</td>
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<td>Daily pilot requirement</td>
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<td>Daily super dispatcher requirement</td>
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<td>Annual wage savings</td>
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<td>Daily super dispatcher requirement</td>
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### Workload Score

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<th>Pushback</th>
<th>Taxi</th>
<th>Take-off</th>
<th>Rejected Take-off</th>
<th>Initial Climb</th>
<th>Cruise to Cruise</th>
<th>Change of Cruise Level</th>
<th>Descent</th>
<th>Holding</th>
<th>Initial Approach</th>
<th>Final Approach</th>
<th>Go-around</th>
<th>Landing</th>
<th>Emergency Descent</th>
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| Pilot Flying         | 56       | 47       | 3      | 83       | 81      | 13       | 51       | 46      | 7       |          |          |          |          |          |          |

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### Levels of Automation

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<td>3 Crew meeting</td>
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<tr>
<td>4 Transfer to aircraft</td>
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<td>Maintenance, ramp, safety check</td>
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<td>Maintenance, ramp</td>
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<td>12 Ready for takeoff</td>
<td>ATC Tower</td>
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<td>13 Climb</td>
<td>ATC Departure</td>
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<td>ATC Enroute</td>
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<td>15 Before top of descent</td>
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<tr>
<td>16 Top of descent</td>
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<td>17 35 minutes before landing</td>
<td>ATC Approach</td>
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<td>18 10000 ft/min climb</td>
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<tr>
<td>19 At transition level</td>
<td>before landing</td>
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<td>21 Final approach fix</td>
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<td>22 10000' 4 miles before landing</td>
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<td>26 Park and shutdown</td>
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* Numbers in brackets [ ] indicate number of checklist items, based on A320 normal operations checklist. CL stands for checklist. Some checklists have been combined for better alignment with process gates in this model.

### Off-Nominals

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<tr>
<th>Off Nominal</th>
<th>#CL Actions</th>
<th>Score</th>
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<tr>
<td>Dual Engine Fail + Ditching</td>
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<td>Avionics Smoke + Emer. Descent</td>
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<tr>
<td>High engine vibration + abnormal igd gear</td>
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<tr>
<td>Pilot Incapacitation</td>
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### New Systems

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<tr>
<td>Incapacitation check system</td>
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<tr>
<td>Digital Parachute</td>
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</tbody>
</table>

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## Costs

### Operating Costs

| Fleet size | 300 |
| Fleet type | NB |
| Pilot group | 3600 |
| Average Pay | $150,000.00 per annum |
| Wage Bill | $540,000,000.00 per annum |
| Departures per day | 5 per aircraft |
| Total flights per day | 1500 |
| Avg stage time | 2 hours |
| Flights per pilot per day | 4 assumed same FDTL |
| Daily pilot requirement | 375 |
| Total pilot group requirement | 1800 |
| New wage bill | $270,043,207 per annum |
| Annual wage savings | $269,956,793 per annum |
| Savings % | 49.99% per annum |

### Acquisition Costs

| Fleet size | 300 |
| Fleet type | WB |
| Pilot group | 3000 |
| Average Pay | $190,000.00 per annum |
| Wage Bill | $570,000,000.00 per annum |
| Departures per day | 1.5 |
| Total flights | 450 |
| Avg stage time | 9 hours |
| Flights per pilot per day | 1 |
| Daily pilot requirement | 563 augmentation included |
| Total pilot group requirement | 1500 |
| New wage bill | $285,000,000 per annum |
| Annual wage savings | $285,000,000 per annum |
| Savings % | 50.00% per annum |

---

### Acquisition Costs

| Fleet size | 300 |
| Fleet type | RJ |
| Pilot group | 3600 |
| Average Pay | $110,000.00 |
| Wage Bill | $396,000,000.00 |
| Departures per day | 7 |
| Total flights | 2100 |
| Avg stage time | 1.25 |
| Flights per pilot per day | 7 |
| Daily pilot requirement | 300 |
| Total pilot group requirement | 1800 |
| New wage bill | $197,960,408 |
| Annual wage savings | $198,039,592 |
| Savings % | 50.001% |

---

### Acquisition Costs

| Fleet size | 300 |
| Fleet type | NB |
| Pilot group | 3600 |
| Average Pay | $150,000.00 per annum |
| Wage Bill | $540,000,000.00 per annum |
| Departures per day | 5 per aircraft |
| Total flights per day | 1500 |
| Avg stage time | 2 hours |
| Flights per pilot per day | 4 assumed same FDTL |
| Daily pilot requirement | 375 |
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| New wage bill | $270,043,207 per annum |
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## 8.5 Architecture ASW – Methods and Scores

### Levels of Automation

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<td>15 Before top of descent</td>
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<td>22 2000’/34 miles before landing</td>
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<tr>
<td>26 Flight report</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>27 Change aircraft/prepare for next flight</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* = numbers in brackets () indicate number of checklist items, based on ASO/nominal operations checklist. CL stands for checklist. Some checklists have been combined for better alignment with process gates in this model.

### Off-Nominals

<table>
<thead>
<tr>
<th>Off Nominal</th>
<th>#CL Actions</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dual Engine Fail + Ditching</td>
<td>41</td>
<td>2.5</td>
</tr>
<tr>
<td>Avionics Smoke + Emer. Descent</td>
<td>36</td>
<td>4</td>
</tr>
<tr>
<td>High engine vibration + abnormal Igd gear</td>
<td>36</td>
<td>5</td>
</tr>
<tr>
<td>Pilot incapacitation</td>
<td>inc + recover</td>
<td>10</td>
</tr>
</tbody>
</table>

### New Systems

<table>
<thead>
<tr>
<th>New systems / capabilities</th>
<th>Cost inc. %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speech recognition</td>
<td>2</td>
</tr>
<tr>
<td>Incapacitation check system</td>
<td>4</td>
</tr>
<tr>
<td>Digital Parachute</td>
<td>10</td>
</tr>
</tbody>
</table>

18.5
### Operating Costs

| Fleet size  | 300  |
| Fleet type  | NB   |
| Pilot group | 3600 |
| Average Pay | $150,000.00 per annum |
| Wage Bill   | $540,000,000 per annum |
| Departures per day | 5  |
| Total flights per day | 1500  |
| Avg stage time | 2 hours |
| Flights per pilot per day | 4 assumed same FOTL |
| Daily pilot requirement | 375 |
| Total pilot group requirement | 1800 |
| New wage bill | $270,043,207 per annum |
| Annual wage savings | $269,956,793 per annum |
| Savings % | 49.99% per annum |

### Acquisition Costs

| Baseline Cost | $100,000,000 |
| Avionics Cost | $25,000,000 |

| Total step change in LoA | 18.5 |
| LoA based cost change % | 46.25 |
| Cost change value | $11,562,500 |
| New systems | 3 |
| New systems cost change % | 16 |
| Cost change value | $4,000,000 |

| Total cost change | $15,562,500 |
| New Avionics Cost | $40,562,500 |
| New Baseline Cost | $115,562,500 |
| 20yr annual spread | $5,778,125 |
| Annual increase fleetwide | $233,437,500 |
| Increase attributable to SPO | $83,437,500 |

| Baseline Cost | $200,000,000 |
| Avionics Cost | $50,000,000 |

| Total step change in LoA | 18.5 |
| LoA based cost change % | 46.25 |
| Cost change value | $23,125,000 |
| New systems | 3 |
| New systems cost change % | 16 |
| Cost change value | $8,000,000 |

| Total cost change | $31,125,000 |
| New Avionics Cost | $81,125,000 |
| New Baseline Cost | $231,125,000 |
| 20yr annual spread | $115,562,500 |
| Annual increase fleetwide | $466,875,000 |
| Increase attributable to SPO | $166,875,000 |

| Baseline Cost | $50,000,000 |
| Avionics Cost | $12,500,000 |

| Total step change in LoA | 18.5 |
| LoA based cost change % | 46.25 |
| Cost change value | $5,781,250 |
| New systems | 3 |
| New systems cost change % | 16 |
| Cost change value | $2,000,000 |

| Total cost change | $7,781,250 |
| New Avionics Cost | $20,281,250 |
| New Baseline Cost | $57,781,250 |
| 20yr annual spread | $2,889,063 |
| Annual increase fleetwide | $116,718,750 |
| Increase attributable to SPO | $43,718,750 |
## Workload Scores

<table>
<thead>
<tr>
<th>Situations</th>
<th>Standing</th>
<th>Push-back</th>
<th>Taxi</th>
<th>Take-off</th>
<th>Rejected Take-off</th>
<th>Initial Climb</th>
<th>Cruise</th>
<th>Change of Cruise Level</th>
<th>Descent</th>
<th>Holding</th>
<th>Initial Approach</th>
<th>Final Approach</th>
<th>Go-around</th>
<th>Landing</th>
<th>Emergency Descent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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</tr>
</tbody>
</table>

### Baseline PF Workload %
- 0.17
- 0.22
- 0.25

### New PF Wload %
- 0.52
- 0.46
- 0.50

### Wload Score
- 6.5
- 4.8
- 10.0
- 21.3 Total

---

**Pilot Flying**

**Pilot Monitoring**

**Automation**

**Ground Pilot**

**Harbor Pilot**

**Super Dispatcher**

133
## 8.6 Architecture AT – Methods and Scores

### Levels of Automation

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>1 Crew arrives</td>
<td>Scheduling</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 Dispatch</td>
<td>Dispatcher</td>
<td>Review/accept</td>
<td>Desktop (Pw, vs, fitplan, et al)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>3 Crew meeting</td>
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<tr>
<td>4 Transfer to aircraft</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>5 Arrive at aircraft</td>
<td></td>
<td>Maintenance, Ramp</td>
<td>Safety check</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 Aircraft status/Status of process Aircraft ready – technical ready of engines</td>
<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>7 Full crew briefing</td>
<td>Cabin Crew</td>
<td>Cabin crew</td>
<td>Output prep, checklists</td>
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<tr>
<td>8 Cabin ready to board</td>
<td>Cabin Crew</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9 All doors closed</td>
<td>Cabin Crew</td>
<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>10 Out of gate (off blocks)</td>
<td>ATC Ramp</td>
<td>Engine start (15)</td>
<td>Engine, Radio comms</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11 Taxi</td>
<td>ATC Ground</td>
<td>Pre-departure (17)</td>
<td>Electric, Hydraulic, Brake, ECAM, AP, APU</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>12 Ready for takeoff</td>
<td>ATC Tower</td>
<td>Before TO (7), Taxi, TO decision</td>
<td>Brakes, Electric, Engine, APU (TCAS)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13 Climb</td>
<td>ATC Departure</td>
<td>After takeoff (8)</td>
<td>Engines, Hydraulic, Electric, Radio comms</td>
<td></td>
<td></td>
<td>Off nominal support, incapacitation backup</td>
</tr>
<tr>
<td>14 Cruise</td>
<td>ATC Enroute</td>
<td>Automation</td>
<td>Electric, Radio cross-check, Radio comms</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 Before top of descent</td>
<td>ATC Approach</td>
<td>before landing (14)</td>
<td>Capabilites/Systems Interaction</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16 Top of descent</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>17 10 minutes before landing</td>
<td>ATC Approach</td>
<td>Before landing (14)</td>
<td>Electric, Hydraulic, Radio comms</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18 10000/8000ft descent</td>
<td>ATC Approach</td>
<td>before landing (14)</td>
<td>Electric, Hydraulic, Radio comms</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19 At transition level</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20 Initial approach Rx</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>21 Final approach Rx</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22 1000 ft-4 miles before landing</td>
<td>ATC Tower</td>
<td>Autonomous decision</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23 Decision height</td>
<td>ATC Tower</td>
<td>Calibrates</td>
<td>FAC, APU, Electric, Radio comms</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24 Landing and rollout</td>
<td>ATC Ground</td>
<td>After landing (18)</td>
<td>Electric, Hydraulic, Engine, Brakes, Electric, Radio comms</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25 Taxi</td>
<td>ATC Ground</td>
<td>After landing (18)</td>
<td>Electric, Hydraulic, Engine, APU, Brakes, Electric, Radio comms</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>26 Park and shutdown</td>
<td>ATC Ramp</td>
<td>Landing (37), Security aircraft (18)</td>
<td>Brakes, Radio comms</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>27 Flight report</td>
<td></td>
<td>Safety, Maintenance report decision</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>28 Change aircraft/Prepare for next flight</td>
<td>Scheduling</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Numbers in brackets () indicate number of checklist items, based on A320 normal operations checklist. CL stands for checklist. Some checklists have been combined for better alignment with process gates in this model.

### Off-Nominals

<table>
<thead>
<tr>
<th>Off Nominals</th>
<th>#CL Actions</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dual Engine Fail + Ditching</td>
<td>41</td>
<td>7</td>
</tr>
<tr>
<td>Avionics Smoke + Emer. Descent</td>
<td>36</td>
<td>7</td>
</tr>
<tr>
<td>High engine vibration + abnormal lgd gear</td>
<td>36</td>
<td>6</td>
</tr>
<tr>
<td>Pilot incapacitation</td>
<td>two humans on board</td>
<td>30</td>
</tr>
</tbody>
</table>

### New Systems

<table>
<thead>
<tr>
<th>New Systems / capabilities</th>
<th>Cost inc. %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auto checklists</td>
<td>2</td>
</tr>
<tr>
<td>Speech recognition</td>
<td>4</td>
</tr>
</tbody>
</table>
## Costs

### Operating Costs

<table>
<thead>
<tr>
<th></th>
<th>Fleet size</th>
<th>Fleet type</th>
<th>Pilot group</th>
<th>Average Pay</th>
<th>Wage Bill</th>
<th>Average tag along pilot pay</th>
<th>Departs per day</th>
<th>Total flights</th>
<th>Flights per crew per day</th>
<th>Flights per tag along pilot per day</th>
<th>Daily pilot requirement</th>
<th>Daily tag along pilot requirement</th>
<th>Total pilot group requirement</th>
<th>New Wage Bill</th>
<th>Annual wage savings</th>
<th>Savings %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>300</td>
<td>WB</td>
<td>3600</td>
<td>$150,000.00</td>
<td>$540,000,000.00</td>
<td>$150,000.00 per annum, flight duty diff</td>
<td>5 per aircraft</td>
<td>1500</td>
<td>6</td>
<td>2 assumed FDTL</td>
<td>250</td>
<td>250</td>
<td>2400 gnd + air even split</td>
<td>$360,000,000</td>
<td>$180,000,000</td>
<td>33.33%</td>
</tr>
</tbody>
</table>

### Acquisition Costs

<table>
<thead>
<tr>
<th></th>
<th>Baseline Cost</th>
<th>Avionics Cost</th>
<th>Total step change in LoA</th>
<th>LoA based cost change %</th>
<th>Cost change value</th>
<th>New systems</th>
<th>New systems cost change %</th>
<th>Cost change value</th>
<th>Total cost change</th>
<th>New Avionics Cost</th>
<th>New Baseline Cost</th>
<th>20yr annual spread</th>
<th>Annual increase fleetwide</th>
<th>Increase attributable to SPO</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$100,000,000</td>
<td>$25,000,000</td>
<td>18.5</td>
<td>46.25</td>
<td>$11,562,500</td>
<td>2</td>
<td>6</td>
<td>$1,500,000</td>
<td>$13,062,500</td>
<td>$38,062,500</td>
<td>$13,062,500</td>
<td>$5,652,125</td>
<td>$495,937,500</td>
<td>$45,937,500</td>
</tr>
<tr>
<td>Fleet size</td>
<td>$100,000,000</td>
<td>$25,000,000</td>
<td>18.5</td>
<td>46.25</td>
<td>$11,562,500</td>
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<td>$38,062,500</td>
<td>$13,062,500</td>
<td>$5,652,125</td>
<td>$495,937,500</td>
<td>$45,937,500</td>
</tr>
<tr>
<td>Total cost change</td>
<td>$262,125,000</td>
<td>$64,750,000</td>
<td>18.5</td>
<td>46.25</td>
<td>$11,562,500</td>
<td>2</td>
<td>6</td>
<td>$1,500,000</td>
<td>$13,062,500</td>
<td>$38,062,500</td>
<td>$13,062,500</td>
<td>$5,652,125</td>
<td>$495,937,500</td>
<td>$45,937,500</td>
</tr>
<tr>
<td>Annual wage savings</td>
<td>$77,520,000</td>
<td>$12,500,000</td>
<td>18.5</td>
<td>46.25</td>
<td>$11,562,500</td>
<td>2</td>
<td>6</td>
<td>$1,500,000</td>
<td>$13,062,500</td>
<td>$38,062,500</td>
<td>$13,062,500</td>
<td>$5,652,125</td>
<td>$495,937,500</td>
<td>$45,937,500</td>
</tr>
<tr>
<td>Savings %</td>
<td>13.60%</td>
<td>21.0%</td>
<td>18.5</td>
<td>46.25</td>
<td>$11,562,500</td>
<td>2</td>
<td>6</td>
<td>$1,500,000</td>
<td>$13,062,500</td>
<td>$38,062,500</td>
<td>$13,062,500</td>
<td>$5,652,125</td>
<td>$495,937,500</td>
<td>$45,937,500</td>
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</tbody>
</table>

### Acquisition Costs

<table>
<thead>
<tr>
<th></th>
<th>Baseline Cost</th>
<th>Avionics Cost</th>
<th>Total step change in LoA</th>
<th>LoA based cost change %</th>
<th>Cost change value</th>
<th>New systems</th>
<th>New systems cost change %</th>
<th>Cost change value</th>
<th>Total cost change</th>
<th>New Avionics Cost</th>
<th>New Baseline Cost</th>
<th>20yr annual spread</th>
<th>Annual increase fleetwide</th>
<th>Increase attributable to SPO</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$100,000,000</td>
<td>$25,000,000</td>
<td>18.5</td>
<td>46.25</td>
<td>$11,562,500</td>
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<td>6</td>
<td>$1,500,000</td>
<td>$13,062,500</td>
<td>$38,062,500</td>
<td>$13,062,500</td>
<td>$5,652,125</td>
<td>$495,937,500</td>
<td>$45,937,500</td>
</tr>
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<td>$25,000,000</td>
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<td>46.25</td>
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<td>$45,937,500</td>
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</table>
Workload Scores

<table>
<thead>
<tr>
<th>Situations</th>
<th>Standing</th>
<th>Rejected</th>
<th>Take off</th>
<th>Take Off</th>
<th>Initial Climb</th>
<th>Climb to Cruise</th>
<th>Cruise</th>
<th>Change of Cruise Level</th>
<th>Descent</th>
<th>Holding</th>
<th>Initial Approach</th>
<th>Final Approach</th>
<th>Go around</th>
<th>Landing</th>
<th>Emergency</th>
<th>Descent</th>
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<tbody>
<tr>
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<tr>
<td>Altitude of aircraft</td>
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<td>Altitude of aircraft</td>
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<tr>
<td>Rate of climb or descent</td>
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Baseline PF Workload %

|          | 0.17 | 0.22 | 0.25 |
| New PF Wload % |
| 0.52 | 0.46 | 0.50 |
| Wload Score |
| 6.5 | 4.8 | 10.0 |
8.7 Architecture V – Methods and Scores

Levels of Automation

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<tbody>
<tr>
<td>1. Crew arrives</td>
<td>Scheduling</td>
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<tr>
<td>2. Dispatch</td>
<td>Dispatcher</td>
<td>Review/Accept</td>
<td>Desktop w/w, wx, fit plan, wt &amp; bal</td>
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<td>3. Crew meeting</td>
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<td>4. Transfer to aircraft</td>
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<td>5. Arrive at aircraft</td>
<td>Gate staff</td>
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<tr>
<td>Aircraft status/Status of aircraft - technical register of airplane</td>
<td>Maintenance, Ramp</td>
<td>Safety check</td>
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<tr>
<td>6. Cabin ready to board</td>
<td>Cabin Crew</td>
<td>Cockpit prep, checklists</td>
<td>(48)</td>
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<tr>
<td>7. Out of gate/off blocks</td>
<td>ATC Ramp</td>
<td>Engine start CL (15)</td>
<td>APU, Electrics, ECAM (fuel, doors), Engines, Radio comms</td>
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<tr>
<td>8. Taxi</td>
<td>ATC Ground</td>
<td>Pre-departure CL (17)</td>
<td>Electrics, Hydraulics, Brakes, ECAM, APU, APU</td>
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<tr>
<td>9. All doors closed</td>
<td>Cabin Crew</td>
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<tr>
<td>10. Ready for takeoff</td>
<td>ATC Tower</td>
<td>Before TO CL (7), Calls, TD decision</td>
<td>Brakes, Electric, Engine, Xpdr (TCAS)</td>
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<tr>
<td>11. Climb</td>
<td>ATC Departure</td>
<td>After takeoff CL (8)</td>
<td>Engines, Hydraulics, Electric, Radio comms</td>
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<tr>
<td>12. Cruise</td>
<td>ATC Enroute</td>
<td>Automation interactions</td>
<td>Autopilot inputs, ACARS (company comms), Radio comms, FMC programming</td>
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<td>14. Top of descent</td>
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<td>15. 15 minutes before landing</td>
<td>ATC Approach</td>
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<td>16. At transition level</td>
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<td>17. Initial approach fix</td>
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<td>18. Final approach fix</td>
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<td>19. Decision height</td>
<td>ATC Tower</td>
<td>Autoland decision</td>
<td>FMC (AIP), Electric, Radiocomms</td>
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<td>20. Landing and rollout</td>
<td>ATC Ground</td>
<td>After landing CL (8)</td>
<td>Hydraulics, Engines, Xpdr, Electric, Brakes, APU, Radio comms</td>
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<td>21. Taxi</td>
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<td>22. Park and shutdown</td>
<td>ATC Ramp</td>
<td>Parking CL (7), Securing aircraft CL (9)</td>
<td>Brakes, Radio comms, CL support, Engines, Electric, ECAM (Fuel), FMC (Air Data, Nav), AP</td>
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<td>23. Flight report</td>
<td>Maintenance</td>
<td>Safety, Maintenance report decision</td>
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<td>24. Change aircraft/prepare for next flight</td>
<td>Scheduling</td>
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* - numbers in brackets ( ) indicate number of checklist items, based on A320 normal operations checklist. CL stands for checklist. Some checklists have been combined for better alignment with process gates in this model.

Off-Nominals

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<tr>
<td>Dual Engine Fail + Ditching</td>
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<tr>
<td>Avionics Smoke + Emer. Descent</td>
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<td>High engine vibration + abnormal lgd gear</td>
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<tr>
<td>Pilot incapacitation</td>
<td>INC + AUTOFT</td>
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New Systems

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<th>Cost inc. %</th>
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<td>Incapacitation check system</td>
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<td>Full Autoflight</td>
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<tr>
<td>Multimodal Interface</td>
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### Costs

#### Operating Costs

| Fleet size | 300 |
| Fleet type | NB  |
| Pilot group | 3600 |
| Average Pay | $150,000.00 |
| Wage Bill | $540,000,000.00 |
| Departures per day | 5 |
| Total flights per day | 1500 |
| Avg stage time | 2 hours |
| Flights per pilot per day | 4 |
| Daily pilot requirement | 375 |
| Total pilot group requirement | 1800 |
| New wage bill | $270,043,207 |
| Annual wage savings | $269,956,793 |
| Savings % | 49.99% |

| Fleet size | 300 |
| Fleet type | WB  |
| Pilot group | 3000 |
| Average Pay | $190,000.00 |
| Wage Bill | $570,000,000.00 |
| Departures per day | 1.5 |
| Total flights | 450 |
| Avg stage time | 9 hours |
| Flights per pilot per day | 1 |
| Daily pilot requirement | 540 |
| Total pilot group requirement | 1440 |
| New wage bill | $273,600,000 |
| Annual wage savings | $296,400,000 |
| Savings % | 52.00% |

| Fleet size | 300 |
| Fleet type | RJ  |
| Pilot group | 3600 |
| Average Pay | $110,000.00 |
| Wage Bill | $396,000,000.00 |
| Departures per day | 7 |
| Total flights | 2100 |
| Avg stage time | 1.25 |
| Flights per pilot per day | 7 |
| Daily pilot requirement | 300 |
| Total pilot group requirement | 1800 |
| New wage bill | $197,960,408 |
| Annual wage savings | $198,039,592 |
| Savings % | 50.01% |

#### Acquisition Costs

| Baseline Cost | $100,000,000 |
| Avionics Cost | $25,000,000 |
| Total step change in LoA | 34.5 |
| LoA based cost change % | 86.25 |
| Cost change value | $21,562,500 |
| New systems | 5 |
| New systems cost change % | 26 |
| Cost change value | $6,500,000 |
| Total cost change | $28,062,500 |
| New Avionics Cost | $53,062,500 |
| New Baseline Cost | $128,062,500 |
| 20 yr annual spread | $6,403,125 |
| Annual increase fleetwide | $420,937,500 |
| Increase attributable to SPO | $270,937,500 |
| Baseline Cost | $200,000,000 |
| Avionics Cost | $50,000,000 |
| Total step change in LoA | 34.5 |
| LoA based cost change % | 86.25 |
| Cost change value | $43,125,000 |
| New systems | 5 |
| New systems cost change % | 26 |
| Cost change value | $13,000,000 |
| Total cost change | $56,125,000 |
| New Avionics Cost | $106,125,000 |
| New Baseline Cost | $256,125,000 |
| 20 yr annual spread | $12,806,250 |
| Annual increase fleetwide | $841,875,000 |
| Increase attributable to SPO | $541,875,000 |
| Baseline Cost | $50,000,000 |
| Avionics Cost | $12,500,000 |
| Total step change in LoA | 34.5 |
| LoA based cost change % | 86.25 |
| Cost change value | $10,781,250 |
| New systems | 5 |
| New systems cost change % | 26 |
| Cost change value | $3,250,000 |
| Total cost change | $14,031,250 |
| New Avionics Cost | $26,531,250 |
| New Baseline Cost | $64,031,250 |
| 20 yr annual spread | $3,201,563 |
| Annual increase fleetwide | $210,468,750 |
| Increase attributable to SPO | $135,468,750 |
Workload Scores

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<th>Initial Climb</th>
<th>Climb to Cruise</th>
<th>Cruise</th>
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<th>Final Approach</th>
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Baseline PF Workload %

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Wload Score 7.7 5.8 11.4 24.9 Total
8.8 Architecture VT — Methods and Scores

Levels of Automation

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<td>Ready for takeoff</td>
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<td>Change aircraft/prep for next flight</td>
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* Numbers in brackets [ ] indicate number of checklist items, based on ASIS normal operations checklist. CL stands for checklist. Some checklists have been combined for better alignment with process gates in this model.

Off-Nominals

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<td>Dual Engine Fail + Ditching</td>
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<td>High engine vibration + abnormal lgd gear</td>
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New Systems

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### Operating Costs

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<table>
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### Acquisition Costs

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<td>$13,531,250</td>
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<td>New Avionics Cost</td>
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<td>New Baseline Cost</td>
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<td>20 yr annual spread</td>
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<td>Increase attributable to SPO</td>
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Workload Scores

### Baseline PF

<table>
<thead>
<tr>
<th>Functions</th>
<th>Take-off</th>
<th>Initial Climb</th>
<th>Cruise</th>
<th>Change of Cruise Level</th>
<th>Descent</th>
<th>Holding</th>
<th>Initial Approach</th>
<th>Final Approach</th>
<th>Go-around</th>
<th>Landing</th>
<th>Emergency Descent</th>
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<tbody>
<tr>
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<td>Rate of climb or descent</td>
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### Pilot Flying

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### Pilot Monitoring

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### Automation

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### Ground Pilot

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### Harbor Pilot

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### Super Dispatcher

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# 8.9 Architecture VS – Methods and Scores

## Levels of Automation

<table>
<thead>
<tr>
<th>Process Gate</th>
<th>Flight Crew Communication</th>
<th>Flight Crew Decision &amp; Actions*</th>
<th>Captain Systems Interaction</th>
<th>Virtual Pilot</th>
<th>Super Dispatcher</th>
<th>Levels of Automation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Crew meet</td>
<td>Dispatcher</td>
<td>Crew local checklist</td>
<td></td>
<td></td>
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<td>NC</td>
</tr>
<tr>
<td>2. Crew prep</td>
<td>Dispatcher</td>
<td>Crew local checklist</td>
<td></td>
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<td>NC</td>
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<tr>
<td>3. Crew briefed</td>
<td>Dispatcher</td>
<td>poly prep checklist</td>
<td></td>
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<td>NC</td>
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<td>4. Arrive at ATC</td>
<td>Maintenance, ramp safety check</td>
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</tr>
<tr>
<td>5. Cabin ready to board</td>
<td>Cabin crew</td>
<td>Gate prep checklist</td>
<td></td>
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<tr>
<td>6. All doors closed</td>
<td>Cabin crew</td>
<td>Off-Nominals</td>
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<td>7. Off-Nominals</td>
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<td>Off-Nominals</td>
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<td>8. Off-Nominals</td>
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<td>Off-Nominals</td>
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<tr>
<td>9. Off-Nominals</td>
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<td>Off-Nominals</td>
<td></td>
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</table>

- **Off-Nominals** indicate number of checklist items, based on 230 normal operations checklist. CL stands for checklist. Some checklists have been combined for better alignment with process gates in this model.

## New Systems

<table>
<thead>
<tr>
<th>New Systems / Capabilities</th>
<th>Cost inc. %</th>
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<tr>
<td>Auto checklists</td>
<td>2</td>
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<td>Speech recognition</td>
<td>4</td>
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<td>Incapacitation check system</td>
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<td>Full Autoflight</td>
<td>12</td>
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<tr>
<td>Multimodal Interface</td>
<td>4</td>
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</table>

- **Note:** The table above represents the levels of automation in the context of flight crew communications and decision-making processes, with a focus on off-nominal events and new system capabilities and their respective costs. The numbers in brackets indicate the level of automation, with higher numbers representing more automated processes. The table is designed to provide a clear and structured overview of the automation levels and their corresponding scores. **New Systems** include capabilities like Auto checklists, Speech recognition, Incapacitation check system, Full Autoflight, Multimodal Interface, and Advanced Datalink, each with a cost incidence percentage associated with them. **Off-Nominals** denote checklist items, primarily based on normal operations, with some checklists combined for better alignment with process gates in the model.
### Operating Costs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Fleet size</td>
<td>300</td>
</tr>
<tr>
<td>Fleet type</td>
<td>WB</td>
</tr>
<tr>
<td>Pilot group</td>
<td>3000</td>
</tr>
<tr>
<td>Average Pay per annum</td>
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</tr>
<tr>
<td>Wage Bill per annum</td>
<td>$570,000</td>
</tr>
<tr>
<td>Average Super Dispatcher pay per annum</td>
<td>$190,000</td>
</tr>
<tr>
<td>Departures per day</td>
<td>1.5</td>
</tr>
<tr>
<td>Total flights</td>
<td>450</td>
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<tr>
<td>Average stage time hours</td>
<td>9</td>
</tr>
<tr>
<td>Flights per pilot per day</td>
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<tr>
<td>Flights per super dispatcher per day</td>
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<tr>
<td>Daily pilot requirement per aircraft</td>
<td>540</td>
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<tr>
<td>Daily super dispatcher requirement per</td>
<td>90</td>
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<tr>
<td>Total pilot group requirement per</td>
<td>1680</td>
</tr>
<tr>
<td>New Wage Bill per annum</td>
<td>$315,200</td>
</tr>
<tr>
<td>Annual wage savings per annum</td>
<td>$250,800</td>
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<tr>
<td>Savings %</td>
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</table>

### Acquisition Costs

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### Costs

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<td>Fleet type</td>
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<tr>
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## Workload Scores

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<th>Takeoff</th>
<th>Rejected Takeoff</th>
<th>Initial Climb</th>
<th>Climb to Cruise</th>
<th>Cruise</th>
<th>Change of Cruise Level</th>
<th>Descent</th>
<th>Holding</th>
<th>Initial Approach</th>
<th>Final Approach</th>
<th>Go Around</th>
<th>Landing</th>
<th>Emergency Descent</th>
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<td>Rate of climb or descent</td>
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<td>Movement of aircraft of the aircraft</td>
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### Baseline PF Workload %

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<th>%</th>
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<tbody>
<tr>
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<td>0.17</td>
</tr>
<tr>
<td>Pushback</td>
<td>0.22</td>
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<td>Taxi</td>
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### New PF Wload %

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<th>%</th>
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<tbody>
<tr>
<td>Standing</td>
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<tr>
<td>Pushback</td>
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<tr>
<td>Taxi</td>
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### Wload Score

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<td>Pushback</td>
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<td>Taxi</td>
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<tr>
<td>Go Around</td>
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---

- **Pilot Flying**
- **Pilot Monitoring**
- **Automation**
- **Ground Pilot**
- **Harbor Pilot**
- **Super Dispatcher**

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## 8.10 Architecture ATS – Methods and Scores

### Levels of Automation

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<tr>
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<td>1. Crew arrival</td>
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<td>7. Cockpit crew arrives</td>
<td>Calculation</td>
<td>Checklist, checklist</td>
<td>Electrics, APU, HVAC, FMC (aircraft data)</td>
<td>Cruise</td>
<td>Cruise</td>
<td>Cruise</td>
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### Off-Nominal

<table>
<thead>
<tr>
<th>Off-Nominal</th>
<th>#CL Actions</th>
<th>Score</th>
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<tbody>
<tr>
<td>Dual Engine Fail + Ditching</td>
<td>41</td>
<td>7</td>
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<tr>
<td>Avionics Smoke + Emer. Descent</td>
<td>36</td>
<td>7</td>
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<tr>
<td>High engine vibration + abnormal Igd gear</td>
<td>36</td>
<td>6</td>
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### New Systems

<table>
<thead>
<tr>
<th>New Systems / Capabilities</th>
<th>Cost inc. %</th>
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<tbody>
<tr>
<td>Auto checklists</td>
<td>2</td>
</tr>
<tr>
<td>Speech recognition</td>
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<td>Advanced Datalink</td>
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## Costs

### Operating Costs

<table>
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<tr>
<td>Fleet size</td>
<td>300</td>
</tr>
<tr>
<td>Average Pay Per Pilot Group</td>
<td>$150,000</td>
</tr>
<tr>
<td>Average Tag Along Pilot Pay</td>
<td>$150,000</td>
</tr>
<tr>
<td>Average Super Dispatcher Pay</td>
<td>$150,000</td>
</tr>
<tr>
<td>Departures per day</td>
<td>5</td>
</tr>
<tr>
<td>Total Flights</td>
<td>1500</td>
</tr>
<tr>
<td>Avg Stage Time</td>
<td>2 hours</td>
</tr>
<tr>
<td>Flights per crew per day</td>
<td>6</td>
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<tr>
<td>Flights per super dispatcher per day</td>
<td>2</td>
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<tr>
<td>Daily pilot requirement</td>
<td>250</td>
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<tr>
<td>Daily tag along pilot requirement</td>
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<td>Daily super dispatcher requirement</td>
<td>75</td>
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<td>Total pilot group requirement</td>
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<td>New Wage Bill</td>
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<tr>
<td>Annual wage savings</td>
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<td>Savings %</td>
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### Acquisition Costs

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<tr>
<td>Average Pay Per Pilot Group</td>
<td>$190,000</td>
</tr>
<tr>
<td>Average Tag Along Pilot Pay</td>
<td>$190,000</td>
</tr>
<tr>
<td>Average Super Dispatcher Pay</td>
<td>$190,000</td>
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<tr>
<td>Departures per day</td>
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<td>Total Flights</td>
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<td>Avg Stage Time</td>
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<td>Flights per pilot per day</td>
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<tr>
<td>Flights per super dispatcher per day</td>
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<tr>
<td>Daily pilot requirement</td>
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<tr>
<td>Daily tag along pilot requirement</td>
<td>486</td>
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<tr>
<td>Daily super dispatcher requirement</td>
<td>45</td>
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<tr>
<td>Total pilot group requirement</td>
<td>2712</td>
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<tr>
<td>New Wage Bill</td>
<td>$515,280,000</td>
</tr>
<tr>
<td>Annual wage savings</td>
<td>$54,720,000</td>
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<tr>
<td>Savings %</td>
<td>9.60%</td>
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8.11 Architecture GdW – Methods and Scores

Levels of Automation

<table>
<thead>
<tr>
<th>Process Gate</th>
<th>Flight Crew Communication</th>
<th>Flight Crew Decisions &amp; Actions*</th>
<th>Captain/Systems Interaction</th>
<th>Ground Based Dedicated Pilot</th>
<th>Wingman</th>
<th>Level of Automation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Crew arrives</td>
<td>Scheduling</td>
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<td></td>
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<tr>
<td>2 Dispatch</td>
<td>Dispatcher</td>
<td>Review/accept</td>
<td>Desktop, y/c, av, fit pin, wt &amp; bal</td>
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<tr>
<td>3 Crew meeting</td>
<td></td>
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</tr>
<tr>
<td>4 Transfer to aircraft</td>
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<tr>
<td>5 Arrive at aircraft</td>
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</tr>
<tr>
<td>Aircraft status/status of aircraft</td>
<td>Maintenance, ramp</td>
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<td></td>
<td></td>
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<td>MC</td>
</tr>
<tr>
<td>6 Flight - technical review of airplane</td>
<td>Flight</td>
<td>Safety check</td>
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<tr>
<td>7 Full crew briefing</td>
<td>Cabin Crew</td>
<td></td>
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<td></td>
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<tr>
<td>8 Cabin ready to board</td>
<td>Cabin Crew</td>
<td>Cockpit prep, checklist</td>
<td></td>
<td>CL Support, Data Comm (clearance), Monitor</td>
<td></td>
<td>MC, AS</td>
</tr>
<tr>
<td>9 All doors closed</td>
<td>Cabin Crew</td>
<td></td>
<td></td>
<td>CL Support, Data Comm, Monitor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 Out of gate/off blocks</td>
<td>ATC Ramp</td>
<td>Engine start (1), (10)</td>
<td></td>
<td></td>
<td></td>
<td>AS</td>
</tr>
<tr>
<td>11 Taxi</td>
<td>ATC Ground</td>
<td>Pre-departure Cl (17)</td>
<td></td>
<td>CL Support, Monitor</td>
<td></td>
<td>AS</td>
</tr>
<tr>
<td>12 Ready for takeoff</td>
<td>ATC Tower</td>
<td>Before TO Cl (7),</td>
<td></td>
<td>SOF calls &amp; actions</td>
<td></td>
<td>AS</td>
</tr>
<tr>
<td>13 Climb</td>
<td>ATC Departure</td>
<td>After takeoff Cl (3)</td>
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<td></td>
<td></td>
<td>AS, ADK after autopilot engaged</td>
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<tr>
<td>14 Cruise</td>
<td>ATC Enroute</td>
<td>Automation</td>
<td></td>
<td>CL Support, Data Comm, Monitor, taxi (the + block)</td>
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<td>Decision Support, SC</td>
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<tr>
<td>15 Before top of descent</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>SC</td>
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<tr>
<td>16 Top of descent</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>SC</td>
</tr>
<tr>
<td>17 5 minutes before landing</td>
<td>ATC Approach</td>
<td>Before landing Cl (18)</td>
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<td>FMC cross check, CL, Support, Monitor</td>
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<tr>
<td>18 1000ft/3-4 miles out</td>
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<td>BOM</td>
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<td>BOM</td>
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<tr>
<td>22 1000ft/3-4 miles before landing</td>
<td>ATC Tower</td>
<td>Autoland decision</td>
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<td>BDM on alternate, ES otherwise</td>
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<td>BDM</td>
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<td>23 Decision height</td>
<td>Callouts</td>
<td>FMC (Alt), Electric, Radio comm</td>
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<td>SOF Callouts, CL Support, Monitor</td>
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<td>BOM</td>
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<tr>
<td>24 Landing and rollout</td>
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<td>BOM</td>
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<tr>
<td>25 Taxi</td>
<td>ATC Ground</td>
<td>After landing Cl (3)</td>
<td></td>
<td></td>
<td></td>
<td>AS</td>
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<tr>
<td>26 Park and shutdown</td>
<td>ATC Ramp</td>
<td>Parking Cl (7), Securing aircraft Cl (9)</td>
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<td>AS</td>
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<td>27 Flight report</td>
<td>Maintenance</td>
<td>Safety, Maintenance</td>
<td></td>
<td></td>
<td></td>
<td>BOM</td>
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<tr>
<td>28 Change aircraft/prepare for next flight</td>
<td>Scheduling</td>
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<td></td>
<td>BOM</td>
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* numbers in brackets ( ) indicate number of checklist items, based on A320 normal operations checklist. Cl stands for checklist. Some checklists have been combined for better alignment with process gates in this model.

Off-Nominals

<table>
<thead>
<tr>
<th>Off Nominals</th>
<th>#CL Actions</th>
<th>Score</th>
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<tbody>
<tr>
<td>Dual Engine Fail + Ditching</td>
<td>41</td>
<td>3</td>
</tr>
<tr>
<td>Avionics Smoke + Emer. Descent</td>
<td>36</td>
<td>4</td>
</tr>
<tr>
<td>High engine vibration + abnormal lgd gear</td>
<td>36</td>
<td>5</td>
</tr>
<tr>
<td>Pilot incapacitation</td>
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New Systems

<table>
<thead>
<tr>
<th>New systems / capabilities</th>
<th>Cost inc. %</th>
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<tbody>
<tr>
<td>Speech recognition</td>
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<tr>
<td>Incapacitation check system</td>
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<tr>
<td>Remote controlled flight</td>
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<td>Advanced datalink</td>
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## Costs

<table>
<thead>
<tr>
<th>Operating Costs</th>
<th>Acquisition Costs</th>
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<tbody>
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<td><strong>Fleet size</strong></td>
<td>$100,000,000</td>
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<tr>
<td>300</td>
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<td>3600</td>
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<tr>
<td><strong>Average Pay</strong></td>
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<td>$150,000.00</td>
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<td>per annum</td>
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<td><strong>Wage Bill</strong></td>
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<td>$540,000,000.00</td>
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<tr>
<td>per annum</td>
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<tr>
<td><strong>Average ground pilot pay</strong></td>
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<tr>
<td>$140,000.00</td>
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<tr>
<td>per annum, flight duty diff</td>
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</tr>
<tr>
<td><strong>Departures per day</strong></td>
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</tr>
<tr>
<td>5</td>
<td></td>
</tr>
<tr>
<td>per aircraft</td>
<td></td>
</tr>
<tr>
<td><strong>Total flights</strong></td>
<td></td>
</tr>
<tr>
<td>1500</td>
<td></td>
</tr>
<tr>
<td><strong>Av. stage time</strong></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
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<tr>
<td>hours</td>
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</tr>
<tr>
<td><strong>Flights per pilot per day</strong></td>
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<td>4</td>
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<tr>
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<td>4</td>
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<tr>
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<tr>
<td><strong>Daily gnd pilot requirement</strong></td>
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<td>375</td>
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<td>3601</td>
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<tr>
<td><strong>New wage bill</strong></td>
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| Acquisition Costs | Baseline Cost                  | $100,000,000 |
|                  | Avionics Cost                  | $25,000,000  |
| **Total step change in LoA** | 0.00 |
| **LoA based cost change %** | 0.00 |
| **Cost change value** | $0.00 |
| **New systems** | 3.00 |
| **New systems cost change %** | 22.00 |
| **Cost change value** | $5,500,000.00 |

| Acquisition Costs | Baseline Cost                  | $200,000,000 |
|                  | Avionics Cost                  | $50,000,000  |
| **Total step change in LoA** | 0.00 |
| **LoA based cost change %** | 0.00 |
| **Cost change value** | $0.00 |
| **New systems** | 3.00 |
| **New systems cost change %** | 22.00 |
| **Cost change value** | $11,000,000.00 |

| Acquisition Costs | Baseline Cost                  | $50,000,000 |
|                  | Avionics Cost                  | $12,500,000 |
| **Total step change in LoA** | 0.00 |
| **LoA based cost change %** | 0.00 |
| **Cost change value** | $0.00 |
| **New systems** | 3.00 |
| **New systems cost change %** | 22.00 |
| **Cost change value** | $2,750,000.00 |

| Acquisition Costs | New Avionics Cost | $30,500,000 |
|                  | New Baseline Cost  | $105,500,000 |
| **Total cost change** | $66,000,000 |
| **20 yr annual spread** | $5,275,000 |
| **Annual increase fleetwide** | $82,500,000 |
| **Increase attributable to SPO** | -$67,500,000 |

| Acquisition Costs | Baseline Cost                  | $200,000,000 |
|                  | Avionics Cost                  | $50,000,000  |
| **Total step change in LoA** | 0.00 |
| **LoA based cost change %** | 0.00 |
| **Cost change value** | $0.00 |
| **New systems** | 3.00 |
| **New systems cost change %** | 22.00 |
| **Cost change value** | $11,000,000.00 |

| Acquisition Costs | Baseline Cost                  | $50,000,000 |
|                  | Avionics Cost                  | $12,500,000 |
| **Total step change in LoA** | 0.00 |
| **LoA based cost change %** | 0.00 |
| **Cost change value** | $0.00 |
| **New systems** | 3.00 |
| **New systems cost change %** | 22.00 |
| **Cost change value** | $2,750,000.00 |

| Acquisition Costs | New Avionics Cost | $30,500,000 |
|                  | New Baseline Cost  | $105,500,000 |
| **Total cost change** | $66,000,000 |
| **20 yr annual spread** | $5,275,000 |
| **Annual increase fleetwide** | $82,500,000 |
| **Increase attributable to SPO** | -$67,500,000 |

| Acquisition Costs | Baseline Cost                  | $50,000,000 |
|                  | Avionics Cost                  | $12,500,000 |
| **Total step change in LoA** | 0.00 |
| **LoA based cost change %** | 0.00 |
| **Cost change value** | $0.00 |
| **New systems** | 3.00 |
| **New systems cost change %** | 22.00 |
| **Cost change value** | $2,750,000.00 |

| Acquisition Costs | New Avionics Cost | $30,500,000 |
|                  | New Baseline Cost  | $105,500,000 |
| **Total cost change** | $66,000,000 |
| **20 yr annual spread** | $5,275,000 |
| **Annual increase fleetwide** | $82,500,000 |
| **Increase attributable to SPO** | -$67,500,000 |

150
### Workload Scores

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<th>Climb to Cruise</th>
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<th>Holding</th>
<th>Initial Approach</th>
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#### Pilot Flying
- Baseline PF Workload %: 0.17, 0.22, 0.25
- New PF Wload %: 0.42, 0.38, 0.41
- Wload Score: 8.1, 5.8, 12.2 (Total 26.1)
# 8.12 Architecture AGdW – Methods and Scores

## Levels of Automation

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<th>Flight Crew Communication</th>
<th>Flight Crew Decisions &amp; Actions</th>
<th>Captain Systems Interaction</th>
<th>Automation</th>
<th>Ground Based Dedicated Pilot</th>
<th>Wingman</th>
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<td>12. Ready for takeoff</td>
<td>STC Switch</td>
<td>Cockpit prep, checks</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13. Takeoff</td>
<td>STC Switch</td>
<td>Radio checks</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14. Approach</td>
<td>STC Switch</td>
<td>Ground checks</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15. Before top of descent</td>
<td>STC Switch</td>
<td>Cockpit checks</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16. Top of descent</td>
<td>STC Switch</td>
<td>Cockpit checks</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17. 1000 ft before landing</td>
<td>STC Switch</td>
<td>Cockpit checks</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18. Decision height</td>
<td>STC Switch</td>
<td>Flight checks, communication</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19. Landing and rollout</td>
<td>STC Switch</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>20. Park and shut down</td>
<td>STC Switch</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>21. Flight report</td>
<td>Maintenance</td>
<td></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>22. Final approach</td>
<td>STC Switch</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>23. Landings and rollout</td>
<td>STC Switch</td>
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<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>24. Park and shut down</td>
<td>STC Switch</td>
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</tr>
<tr>
<td>25. Flight report</td>
<td>Maintenance</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

* Numbers in brackets ( ) indicate number of checklist items, based on A320 normal operations checklist. CL stands for checklist. Some checklists have been combined for better alignment with process gates in this model.

## Off-Nominals

<table>
<thead>
<tr>
<th>Off Nominal</th>
<th>#CL Actions</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dual Engine Fail + Ditching</td>
<td>41</td>
<td>3.5</td>
</tr>
<tr>
<td>Avionics Smoke + Emer. Descent</td>
<td>36</td>
<td>5</td>
</tr>
<tr>
<td>High engine vibration + abnormal lgd gear</td>
<td>36</td>
<td>6</td>
</tr>
<tr>
<td>Pilot incapacitation</td>
<td>Human on the grd can fly</td>
<td>25</td>
</tr>
</tbody>
</table>

## New Systems

<table>
<thead>
<tr>
<th>New systems / capabilities</th>
<th>Cost inc. %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speech recognition</td>
<td>2</td>
</tr>
<tr>
<td>Incapacitation check system</td>
<td>4</td>
</tr>
<tr>
<td>Remote controlled flight</td>
<td>7</td>
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### Costs

#### Operating Costs

<table>
<thead>
<tr>
<th>Fleet size</th>
<th>300</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fleet type</td>
<td>WB</td>
</tr>
<tr>
<td>Pilot group</td>
<td>3600</td>
</tr>
<tr>
<td>Average Pay</td>
<td>$150,000.00 per annum</td>
</tr>
<tr>
<td>Wage Bill</td>
<td>$540,000,000.00 per annum</td>
</tr>
<tr>
<td>Average ground pilot pay</td>
<td>$140,000.00 per annum, flight duty diff</td>
</tr>
<tr>
<td>Departures per day</td>
<td>5 per aircraft</td>
</tr>
<tr>
<td>Total flights</td>
<td>1500</td>
</tr>
<tr>
<td>Avg stage time</td>
<td>2 hours</td>
</tr>
<tr>
<td>Flights per pilot per day</td>
<td>4</td>
</tr>
<tr>
<td>Flights per ground pilot per day</td>
<td>4</td>
</tr>
<tr>
<td>Daily pilot requirement</td>
<td>375</td>
</tr>
<tr>
<td>Daily ground pilot requirement</td>
<td>375</td>
</tr>
<tr>
<td>Total pilot group requirement</td>
<td>3601</td>
</tr>
<tr>
<td>New wage bill</td>
<td>$522,140,000 per annum</td>
</tr>
<tr>
<td>Annual wage savings</td>
<td>$17,860,000 per annum</td>
</tr>
<tr>
<td>Savings %</td>
<td>3.31%</td>
</tr>
</tbody>
</table>

#### Acquisition Costs

<table>
<thead>
<tr>
<th>Fleet size</th>
<th>300</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fleet type</td>
<td>WB</td>
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<tr>
<td>Pilot group</td>
<td>3600</td>
</tr>
<tr>
<td>Average Pay</td>
<td>$150,000.00 per annum</td>
</tr>
<tr>
<td>Wage Bill</td>
<td>$540,000,000.00 per annum</td>
</tr>
<tr>
<td>Average ground pilot pay</td>
<td>$140,000.00 per annum, flight duty diff</td>
</tr>
<tr>
<td>Departures per day</td>
<td>5 per aircraft</td>
</tr>
<tr>
<td>Total flights</td>
<td>1500</td>
</tr>
<tr>
<td>Avg stage time</td>
<td>2 hours</td>
</tr>
<tr>
<td>Flights per pilot per day</td>
<td>4</td>
</tr>
<tr>
<td>Flights per ground pilot per day</td>
<td>4</td>
</tr>
<tr>
<td>Daily pilot requirement</td>
<td>375</td>
</tr>
<tr>
<td>Daily ground pilot requirement</td>
<td>375</td>
</tr>
<tr>
<td>Total pilot group requirement</td>
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</tr>
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<td>$522,140,000 per annum</td>
</tr>
<tr>
<td>Annual wage savings</td>
<td>$17,860,000 per annum</td>
</tr>
<tr>
<td>Savings %</td>
<td>3.31%</td>
</tr>
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</table>
8.13 Architecture AGh – Methods and Scores

Levels of Automation

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Crew arrives</td>
<td>Scheduling</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 Dispatch</td>
<td>Dispatcher</td>
<td>Review/accept</td>
<td>Desktop s/w, en, fit pin, wi &amp; bal</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 Crew meeting</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 Transfer to aircraft</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 Arrive at aircraft</td>
<td>Gate staff</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 Aircraft status/Status of aircraft ready - technical register of airplane</td>
<td>Maintenance, Ramp</td>
<td>Safety check</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 Full crew briefing</td>
<td>Cabin Crew</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 Cabin ready to board</td>
<td>Cabin Crew</td>
<td>Co-pilot prep, checklists</td>
<td>Electrics, APU, Hydraulics, FMC (Air data, Nav, IF/IFr), Cabin environment, ECAM</td>
<td>Cl Support, Data Comm (clearance), Monitor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9 All doors closed</td>
<td>Cabin Crew</td>
<td>(48)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 Out of gate off blocks</td>
<td>ATC Ramp</td>
<td>Engine start (C) (15)</td>
<td>Electrics, Hydraulics, Brakes, ECAM, APU, Fit Controls, Radio centres</td>
<td>Cl Support, Data Comm, Monitor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11 Taxi</td>
<td>ATC Ground</td>
<td>Pre-departure (CL 17)</td>
<td>(Electrics, Hydraulics, Brakes, ECAM, APU)</td>
<td>Cl Support, Monitor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12 Ready for takeoff</td>
<td>ATC Tower</td>
<td>Before TO (F)</td>
<td>(Electrics, Hydraulics, Brakes, ECAM, APU)</td>
<td>In-capacitation check</td>
<td>SOP Actions, Callouts</td>
<td>BDM</td>
</tr>
<tr>
<td>13 Climb</td>
<td>ATC Departure</td>
<td>After takeoff (C) (8)</td>
<td>(Electrics, Hydraulics, Electric, Radio centres)</td>
<td>Fi Controls, In-capacitation Check, Cl Support, Data Comm, Monitor, Wi (Rack)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14 Cruise</td>
<td>ATC Execute</td>
<td>Automation:</td>
<td>(Electrics, Nav, FMC programming &amp; check, Radio centres)</td>
<td>Fi Controls, In-capacitation Check, FMC, Phone, Cl Support, Monitor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 Pre-to-depart</td>
<td>ATC Execute</td>
<td>Automation:</td>
<td>(Electrics, Nav, FMC programming &amp; check, Radio centres)</td>
<td>Fi Controls, In-capacitation Check, FMC, Phone, Cl Support, Monitor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16 Taxi</td>
<td>ATC Ground</td>
<td>Before landing (CL 18)</td>
<td>(Electrics, Hydraulics, Radio centres)</td>
<td>Fi Controls, In-capacitation Check</td>
<td>Cl Support, Monitor</td>
<td></td>
</tr>
<tr>
<td>17 Initial approach fix</td>
<td>ATC Tower</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18 9000 ft: Initial approach fix</td>
<td>ATC Approach</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19 3000 ft: Initial approach fix</td>
<td>ATC Tower</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20 Final approach fix</td>
<td>ATC Tower</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21 Final approach fix</td>
<td>ATC Tower</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22 200 ft: 3 miles before landing</td>
<td>ATC Tower</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>23 Decision height</td>
<td>ATC Tower</td>
<td>Callouts</td>
<td>FMC (Air), Electrics, Radio centres</td>
<td>SOP Callouts, Fi Controls, In-capacitation Check</td>
<td>Cl Support, Monitor</td>
<td></td>
</tr>
<tr>
<td>24 Takeoff and rollout</td>
<td>ATC Ground</td>
<td>After landing (C) (9)</td>
<td>(Hydraulics, Engines, APU, Radio centres)</td>
<td>SOP Actions, Callouts</td>
<td>Cl Support, Monitor</td>
<td>BDM</td>
</tr>
<tr>
<td>25 Taxi</td>
<td>ATC Ground</td>
<td>After landing (C) (9)</td>
<td>(Hydraulics, Engines, APU, Radio centres)</td>
<td>SOP Actions, Callouts</td>
<td>Cl Support, Monitor</td>
<td>BDM</td>
</tr>
<tr>
<td>26 Park and shutdown</td>
<td>ATC Ramp</td>
<td>Parking CL (7), Securing aircraft CL (9)</td>
<td>(Electrics, Brakes, Radio centres)</td>
<td>Engines, Electrics, ECAM (Fuel), FMC (Air data, Nav, IF/IFr), APU</td>
<td>Cl Support, Monitor</td>
<td></td>
</tr>
<tr>
<td>27 Flight report</td>
<td>Maintenance</td>
<td>Safety, Maintenance report decision</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>28 Change aircraft/prepare for next flight</td>
<td>Scheduling</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* - numbers in brackets () indicate number of checklist items, based on A320 normal operations checklist. CL stands for checklist. Some checklists have been combined for better alignment with process gates in this model.

Off-Nominals

<table>
<thead>
<tr>
<th>Off Nominals</th>
<th>#CL Actions</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dual Engine Fall + Ditching</td>
<td>41</td>
<td>2</td>
</tr>
<tr>
<td>Avionics Smoke + Emer. Descent</td>
<td>36</td>
<td>3.5</td>
</tr>
<tr>
<td>High engine vibration + abnormal lgd gear</td>
<td>36</td>
<td>6</td>
</tr>
<tr>
<td>Pilot incapacitation</td>
<td>Incap + recover</td>
<td>22.5</td>
</tr>
</tbody>
</table>

New Systems

<table>
<thead>
<tr>
<th>New systems / capabilities</th>
<th>Cost inc. %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incapacitation check system</td>
<td>4</td>
</tr>
<tr>
<td>Remote controlled flight</td>
<td>7</td>
</tr>
<tr>
<td>Auto checklist system</td>
<td>2</td>
</tr>
</tbody>
</table>
## Costs

### Operating Costs

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fleet size</td>
<td>300</td>
</tr>
<tr>
<td>Fleet type</td>
<td>WB</td>
</tr>
<tr>
<td>Pilot group</td>
<td>3600</td>
</tr>
<tr>
<td>Average Pay</td>
<td>$150,000.00 per annum</td>
</tr>
<tr>
<td>Wage Bill</td>
<td>$40,000,000.00 per annum</td>
</tr>
<tr>
<td>Average harbor pilot pay</td>
<td>$180,000.00 per annum, flight duty diff</td>
</tr>
<tr>
<td>Departures per day</td>
<td>5 per aircraft</td>
</tr>
<tr>
<td>Total flights</td>
<td>1500</td>
</tr>
<tr>
<td>Avg stage time</td>
<td>2 hours</td>
</tr>
<tr>
<td>Flights per pilot per day</td>
<td>12</td>
</tr>
<tr>
<td>Daily pilot requirement</td>
<td>375</td>
</tr>
<tr>
<td>Daily gnd pilot requirement</td>
<td>125</td>
</tr>
<tr>
<td>Total pilot group requirement</td>
<td>2400</td>
</tr>
<tr>
<td>New wage bill</td>
<td>$384,000,000 per annum</td>
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<tr>
<td>Annual wage savings</td>
<td>$156,000,000 per annum</td>
</tr>
<tr>
<td>Savings %</td>
<td>28.89%</td>
</tr>
</tbody>
</table>

| Fleet size                        | 300                    |
| Fleet type                        | WB                     |
| Pilot group                       | 3000                   |
| Average Pay                       | $190,000.00 per annum  |
| Wage Bill                         | $570,000,000.00 per annum |
| Average harbor pilot pay          | $240,000.00 per annum  |
| Departures per day                | 1.5                    |
| Total flights                     | 450                    |
| Avg stage time                    | 9 hours                |
| Flights per pilot per day         | 12                     |
| Daily pilot requirement           | 565                    |
| Daily gnd pilot requirement       | 38                     |
| Total pilot group requirement     | 1600                   |
| New Wage bill                     | $309,400,000 per annum |
| Annual wage savings               | $260,600,000 per annum |
| Savings %                         | 45.72%                 |

### Acquisition Costs

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Baseline Cost</td>
<td>$100,000,000</td>
</tr>
<tr>
<td>Avionics Cost</td>
<td>$25,000,000</td>
</tr>
<tr>
<td>Total step change in LoA</td>
<td>9</td>
</tr>
<tr>
<td>LoA based cost change %</td>
<td>22.50</td>
</tr>
<tr>
<td>Cost change value</td>
<td>$5,625,000</td>
</tr>
<tr>
<td>New systems</td>
<td>3</td>
</tr>
<tr>
<td>New systems cost change %</td>
<td>13</td>
</tr>
<tr>
<td>Cost change value</td>
<td>$3,250,000</td>
</tr>
<tr>
<td>Total cost change</td>
<td>$8,875,000</td>
</tr>
<tr>
<td>New Avionics Cost</td>
<td>$33,875,000</td>
</tr>
<tr>
<td>New Baseline Cost</td>
<td>$108,875,000</td>
</tr>
<tr>
<td>20 yr annual spread</td>
<td>$52,721,750</td>
</tr>
<tr>
<td>Annual increase fleetwide</td>
<td>$133,125,000</td>
</tr>
<tr>
<td>Increase attributable to SPO</td>
<td>-$16,875,000</td>
</tr>
<tr>
<td>Baseline Cost</td>
<td>$200,000,000</td>
</tr>
<tr>
<td>Avionics Cost</td>
<td>$50,000,000</td>
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<tr>
<td>Total step change in LoA</td>
<td>9</td>
</tr>
<tr>
<td>LoA based cost change %</td>
<td>22.50</td>
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<tr>
<td>Cost change value</td>
<td>$11,250,000</td>
</tr>
<tr>
<td>New systems</td>
<td>3</td>
</tr>
<tr>
<td>New systems cost change %</td>
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<tr>
<td>Cost change value</td>
<td>$6,500,000</td>
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<tr>
<td>Total cost change</td>
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<tr>
<td>New Avionics Cost</td>
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<tr>
<td>New Baseline Cost</td>
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<tr>
<td>20 yr annual spread</td>
<td>$10,887,500</td>
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<tr>
<td>Annual increase fleetwide</td>
<td>$266,250,000</td>
</tr>
<tr>
<td>Increase attributable to SPO</td>
<td>-$33,750,000</td>
</tr>
</tbody>
</table>

| Baseline Cost                     | $50,000,000            |
| Avionics Cost                     | $12,500,000            |
| Total step change in LoA          | 9                     |
| LoA based cost change %           | 22.50                  |
| Cost change value                 | $2,812,500             |
| New systems                       | 3                     |
| New systems cost change %         | 13                    |
| Cost change value                 | $1,625,000             |
| Total cost change                 | $4,437,500             |
| New Avionics Cost                 | $16,957,500            |
| New Baseline Cost                 | $94,437,500            |
| 20 yr annual spread               | $2,721,875             |
| Annual increase fleetwide         | $66,562,500            |
| Increase attributable to SPO      | -$8,437,500            |
### Workload Score

The Workload Score table below represents the workload scores for various flight phases and situations.

<table>
<thead>
<tr>
<th>Situation</th>
<th>Baseline PF Workload %</th>
<th>New PF Wload %</th>
<th>Wload Score</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.17</td>
<td>0.43</td>
<td>7.9</td>
</tr>
<tr>
<td></td>
<td>0.22</td>
<td>0.44</td>
<td>5.0</td>
</tr>
<tr>
<td></td>
<td>0.25</td>
<td>0.5</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>22.9 Total</td>
</tr>
</tbody>
</table>

**Key Points:**
- Baseline Pilot Flying Workload %: 0.17, 0.22, 0.25
- New Pilot Workload %: 0.43, 0.44, 0.5
- Wload Score: 7.9, 5.0, 10
- Total Wload Score: 22.9
### 8.14 Architecture AGhW – Methods and Scores

#### Levels of Automation

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* numbers in brackets () indicate number of checklist items, based on XGBI normal operations checklist. CL stands for checklist. Some checklists have been combined for better alignment with process gates in this model.

## Off-Nominals

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<th>#CL Actions</th>
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<td>Dual Engine Fall + Ditching</td>
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<td>Avionics Smoke + Emer. Descent</td>
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<td>High engine vibration + abnormal lgd gear</td>
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<td>Pilot incapacitation</td>
<td>incp + recover</td>
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## New Systems

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<td>Remote controlled flight</td>
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## Costs

### Operating Costs

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<td>Wage Bill per annum</td>
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<tr>
<td>Average harbor pilot pay per annum, flight duty diff</td>
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<td>Departures per day</td>
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<td>Total flights</td>
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<td>Avg stage time</td>
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<td>Savings % per annum</td>
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<table>
<thead>
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### Acquisition Costs

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### Acquisition Costs

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### Acquisition Costs

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### Workload Score

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<th>Push back</th>
<th>Taxi</th>
<th>Take-off</th>
<th>Rejecte</th>
<th>Take-off</th>
<th>Initial Climb</th>
<th>Cruise to Cruise</th>
<th>Change of Cruise Level</th>
<th>Descent</th>
<th>Holding</th>
<th>Initial Approach</th>
<th>Final Approach</th>
<th>Go-around</th>
<th>Landing</th>
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