Single-Pilot Aircraft in Commercial Air Transport Operations: A Comparison of Potential Architectures

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Single pilot operations (SPO) in commercial air transport presents a range of benefits and challenges, but there is a need to define architectures and compare them in different operational contexts. Here, we identified various combinations of architectural decisions based on the literature, and compared them to current operations—in different operating contexts—on a safety versus cost trade space. Safety was defined as a function of pilot nominal operations workload, handling of off nominal situations, and pilot incapacitation, while cost was defined as a combination of acquisition and operating costs. Our analysis suggests 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 architectures in the trade space. The analysis also reveals that regional aircraft may be prime candidates to move to SPO first, as most regional architectures generate positive savings.

I. Introduction to the Problem

A. Technological Progress and De-crewing

The advent of the glass cockpit and increasing levels of automation within the flight deck have progressively reduced flight crew required to operate an aircraft. Taking this progress of automation to its logical conclusion, some have predicted that pilotless passenger aircraft will be available in two decades away [1], while more pessimistic commentators suggest that they will arrive in the next 100 years [2]. Regardless, this paper 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 [3] have already announced their intent to offer aircraft with single pilot capabilities somewhere beyond

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2020. 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.

A number of factors support the case for single pilot operations. First, labor costs are the highest component of a passenger airline's total operating costs. In 3Q 2015, labor costs for American passenger airlines were 30.7% of its operating costs, compared to fuel costs which were 18.9%. Second is the prospect of a pilot shortage reported in news articles. 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 [3]. It is argued that fewer people choose commercial flying as a career option due to a combination of low wages at the entry level and tightening entry barriers in terms of experience [4]. Universal adoption of single pilot operations in commercial air transport could help match supply and demand of pilots, or at least narrow the gap. Conversely, there is also the possibility that SPO would lead to lower costs per seat-kilometer [2], which in turn can lower ticket costs and spur demand, increasing the number of flights and keeping the pilot requirement steady. In sum, single pilot operations can be viewed favorably from the perspective of reducing operating costs, provided that architectures are chosen carefully so as not to incur new additional costs that wipe out the marginal benefits.

B. Safety Considerations

Another consideration for the adoption of SPO is the impact on safety. The safety of passenger aircraft has increased over time due to a few developments. Newer technologies have increased the reliability of systems [5] while managing an increase in complexity and capability. Starting with rudimentary one-axis autopilots, automation is now capable of performing most of the tasks involved in flight, including very specific tasks which require high accuracy and performance, e.g., RNAV approaches and autonomous Traffic Resolution maneuvers. Another contributor is aviation's culture of safety where lessons learnt from mishaps are assessed thoroughly, disseminated widely, and assimilated quickly. One noteworthy trend is that actions by the crew account for 62% of the hull-loss accidents in the decade between 1994 and 2003 [6], and the trend has continued since then. Since human error is the biggest cause of accidents, proponents of unmanned passenger aircraft [7] argue that eliminating the pilot is the way forward for safer operations. However, passengers may resist SPO: a survey in the UK showed that only half of the respondents indicated their willingness to be on a single-pilot, short-haul flight [8].

Setting aside this debate, SPO presents a unique challenge in terms of safety. Although the number of humans available to make errors are reduced, the remaining human may now be even more prone to error. As aviation progresses towards a fully autonomous future, it will be important to maintain levels of workload at or below what a single crewmember experiences today. Increased automation also brings up the challenge 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 [9]. A number of recent accidents (e.g., Air France 447, Indonesia Air Asia 8501, Asiana 214 [10]) show actions by the flight crew that run contrary to what is taught as basic flight skills. All three cases also show that the crews were, at the very least, only partially aware of what the automation was doing. Finally, there is the loss of collaboration between crew members in decision making. Events 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 Crew Resource Management 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.

C. Paper outline

This paper aims to take an integrative approach towards designing a possible system architecture for a single-pilot commercial transport aircraft. In the Literature Review, we look at proposed architectures for single pilot operations, and determine 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). In Feasibility and Viability, we examine the commercial and safety pros and cons of single pilot aircraft at a high level, identifying key challenges ahead. The Methods section proposes a baseline model against which the SPO architectures can be compared against, and outlines the methods and assumptions made in quantifying architectural characteristics. The section on Architecture Decisions proposes high-level architectural decisions, incorporating reasonable assumptions of anticipated technological progress as well as current research trends in SPO. In Results, we offer an example explication of the method using the authors' scoring of each architecture, to compare various combinations of these architectural decisions on a cost versus safety tradespace.

II. Literature Review

A. Business Case and Viability

In terms of business case and viability, the literature identifies a number of challenges in moving to SPO. Ref. [2] describes issues with automation (failure, appropriate level, communication with humans), communication and conflict management between different agents in SPO, and the social context (e.g., boredom, down-time) and workload of the single pilot. Ref. [11] argues that the greatest challenges lie in developing user interfaces, integrating technologies, and creating new concepts of operation. In contrast, Ref. [5] 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.

Approaches to address these challenges focus either on technology or humans. Ref. [12] identifies speech recognition, electronic moving maps, and agent-based modeling as playing a key role in helping develop SPO procedures. Ref. [5] describes 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. Ref. [11] recommends that a ground-based control station and crew would be most effective in reducing dependencies on the single pilot; Ref. [13] considers this architecture as the most feasible.

B. Architectures and Analysis

Both automation and ground-based crew members have been described to help decrease the mental workload of single pilots without sacrificing their situational awareness. Ref. [6] proposes four different ways single pilots can interact with automation to achieve this goal: (1) as another human that provides knowledge-based reasoning, information, and behavior for non-time critical tasks; (2) as a domesticated animal like a horse that obeys the pilot's commands through a limited means of communication and can challenge a pilot's dangerous behavior for time-critical tasks; (3) as an extension of the pilot's body that enhances, empowers and extends the pilot's capabilities for skill-based tasks; and (4) as a tool for task-specific scenarios.

When considering ground-based approaches, Ref. [14] determined that a ground-based crew member does not need much situational awareness to provide effective assistance when called in to play the role of a first officer as long as the ground station adequately displays information related to the aircraft, its systems, and its environment. However, Ref. [15] found that an air-ground approach to SPO was not as successful as baseline architectures in helping crew fly difficult off-nominal scenarios, partially due to the design of the collaboration tools. Air-ground teams will also face challenges in dividing tasks between the airborne and ground-based pilots; it is also unknown how many aircraft a ground-based pilot can handle at one time [16,17].

When considering architectures, Ref. [18] 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 [19], and may be continued when the cause of interruption is no longer a factor. The authors propose a process-based model of flight crew tasks as a series of process gates and decision points. This model 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. From the point of view of SPO, the detailed flight crew task process model can serve as a basis for evaluating SPO-induced changes. As a first step, this model can 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.

C. Safety

Safety issues related to SPO point to not only the pilot, but also to other people responsible for the operation and maintenance of flights. Based upon their conclusion that the 24 Mar 2015 crash of GermanWings flight 9525 was deliberately caused by the first officer, the French BEA called for EASA to conduct pilot incapacitation studies with an emphasis on incapacitation due to mental health issues, as well as clearer definitions for the re-issue of medical certificates when a revalidation is denied due to a mental health episode [20]. Notably, prior Safety requirements (created 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, which presents greater concerns for SPO.

The Greek AAIASB determined that Helios Airways flight 522 crashed on 14 Aug 2005 because incorrect actions by the flight and maintenance crew led to the malfunction in the pressurization system, thereby causing hypoxia in the pilots [21]. 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. As described, several of the safety recommendation have direct consequences for SPO (CRM, checklists, and monitoring of automation warnings), while others would not be impacted by SPO (maintenance procedures).

D. Research Gaps

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. Even the NASA SPO steering committee defined SPO only in terms of reducing the number of flight crew to one—without providing architectural context—and did not examine in detail the possible architectures for achieving SPO. Also missing from the research landscape is the impact on and from second- and third-level architectural issues, e.g., crew scheduling, training [22], and other additional costs that may be incurred. This gap may be due to the fact that SPO is still at least one generation of aircraft away from being realized, but regardless, different architectures for different operators need to be evaluated.

III. Feasibility and Viability of Single Pilot Operations in Commercial Air Transport

This section of the paper analyzes the viability of SPO at a systems level, focusing on trends and challenges in safety and business impact. From the perspective of management, the case for SPO should be built by exploring whether the pilot as a system operating the airplane needs to be scrutinized because (s)he now becomes a single point of failure. At a high level, the viability of SPO effectively concerns 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?

A. Can commercial air transport operations be safely conducted with a single pilot operating the aircraft?

This question boils down to redundancy and safety. Currently, the two pilots operating an airplane extend the concept of redundancy that is found in practically every other subsystem on board the aircraft. Depending on the chosen architecture, 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. Finally, we must identify safety issues that may uniquely affect single pilot operations. There are many dimensions to safety - in this analysis we consider only two contributors to safety: pilot workload (in nominal and off nominal situations) and pilot incapacitation.

1. Pilot Workload

Because removing the second pilot may increase the workload on the remaining pilot, it has been suggested that the on-board automation may take on some or all of the tasks of the second pilot, depending on the actual architectural configuration [2,11,23]. Such replacement may pose many challenges [6]. For instance, full replacement by automation presumes the necessary technology is on the horizon. In addition, such replacement removes the social interaction that prevents boredom and keeps the crew alert on long cruise segments. Thus, a real-world architecture for SPO will likely fall somewhere in the spectrum between fully human to fully autonomous. From a safety perspective, consideration of pilot workload is not only composed of nominal operations - it must also evaluate pilot workload in off-nominal situations such as communication systems failures.

Given this assumption, the pilot workload may change in two directions. As previously described, the responsibility to manage additional systems can place an unsafe burden on the pilot. In particular, extended periods of managing systems may degrade the pilot's ability to deal with off-nominal conditions [6] and systems failures [12]. For example, on AF447 the concern was that reliance on automation to manage most of the flight had led to pilots missing something as basic as the fact that they had stalled the airplane. Alternatively, the pilot workload may decrease or go away entirely, resulting in a decrease in vigilance and reduced situation awareness [11]. For example, a pilot might not need to crosscheck the second pilot's actions, especially if the pilot receives more consistent performance from automation than they do when flying with different human F/Os every day (although this may raise other failure modes of automation operating out of the designed-to context).

2. Pilot Incapacitation

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, very little is known about the effects of incapacitation in a single pilot operation scenario. In SPO, pilot incapacitation can be broken down to two challenges [5]: detecting the incapacitation and the recovery of the aircraft after incapacitation. According to Evans and Radcliffe (2012), 4.3% of UK pilots in 2004 with a valid UK/JAR class 1 medical certificate underwent episodes where they were at least temporarily unable to operate an aircraft. Dr. R. Michael Norman of the Boeing Company determined that from January 1987 to December 2006, Part 121 air transport operations had an incapacitation rate of 10 events for every billion hours flown [2]. In SPO, where the pilot as a system has no redundancy, this incapacitation rate would cause the reliability rate to fall below the required level of less than one event per billion hours flown.

B. Is it financially desirable to operate commercial transport aircraft with only a single pilot?

This question constitutes the financial aspect of the problem. When discussing SPO from a business perspective as opposed to a purely technical one, it is important to consider the context of operation, as well as a few real-world operating constraints. In this section, our examination of the business case for SPO is limited to large narrowbodies (A320 class aircraft) on one hand and all widebody (twin-aisle) types on the other because data were not available for airlines operating a fleet consisting entirely of regional aircraft (like the Embraer E-Jets, or Bombardier CRJs). However, the potential architectures for SPO were considered for all three aircraft types, and in subsequent sections, we develop forward-going financial models for all three.

For purposes of the study, we used 2014 data to look at the all-narrowbody fleet of Southwest Airlines [24] and the all-widebody fleet of Emirates Airlines. Southwest incurs a cockpit cost of $807 per block hour [25]. Assuming a conservative 65-35 split between Captain and F/O costs, the airline spends $282.45 per block hour on the F/O—or $1694.7 per duty day, assuming 3 daily sectors of two hours long. Ref. [26] calculates an assumed 2379 pilots are on duty on an average day. By moving to SPO, this figure can be reduced by 50% because Southwest does not need crew augmentation: their longest sector (Baltimore-Oakland) is within FDTL limitations. For 1190 first officer positions eliminated, the daily savings work out to $2,016,693, leading to an annual savings of $736 million. Alternatively, if all pilots are at 14-hour FDTLs operating five daily average sectors, the savings work out to $365 million annually. Not taking into account real-world constraints imposed by seniority and FDTL actuals, we therefore calculate that Southwest Airlines can save in the range of 365-736 million dollars.

In contrast, Ref. [26] projects SPO savings of $190.5 million annually for Emirates. The annual savings increase to $247.2 million if we assume an architecture where constant monitoring is not required in cruise phase, and that ULH flights can be operated with two crew and all other flights with one.

1. *Identifying New Costs*

Given the different architectural possibilities discussed so far, SPO may give rise to new costs due to the needs of the operating architecture. First, SPO architecture requires the creation of new operators such as super dispatchers, ground-based pilots, ground-based system specialists, or other ground-based operators. Second, new infrastructure must be built and operated. If ground-based crew members are involved, the number of needed stations will vary depending on the architecture. A harbor pilot architecture [27] may only need ground stations near major airports, while a dedicated ground pilot architecture would require ground stations based on the range of communications relative to the length of the flight. Finally, there is the issue of pilot shortage, which is one of the motivations for moving towards SPO. While single pilot aircraft will certainly require less of a labor force to operate, the effect on shortage may not be linear. Placing a pilot in sole control of an aircraft may require more money for training, which may further decrease the attractiveness of flying as a profession and increase operating costs by pushing salaries upwards.

IV. Methods

A. Introduction and Goals

The goal of building a baseline model of today's flight operations is to enable comparisons of future SPO architectures. To compare these parameters, it is important to first take a look at what determines safety and cost. As identified in Section III, a first order safety analysis should at minimum consider pilot workload in nominal operations, as well as the ability to handle off-nominal situations and pilot incapacitation. Cost is determined by the increase in complexity, reliability, and redundancy of aircraft systems driving acquisition costs, and the number of operators and amount of infrastructure driving operation costs.

B. Approach and Assumptions

1. Workload in Nominal Operations

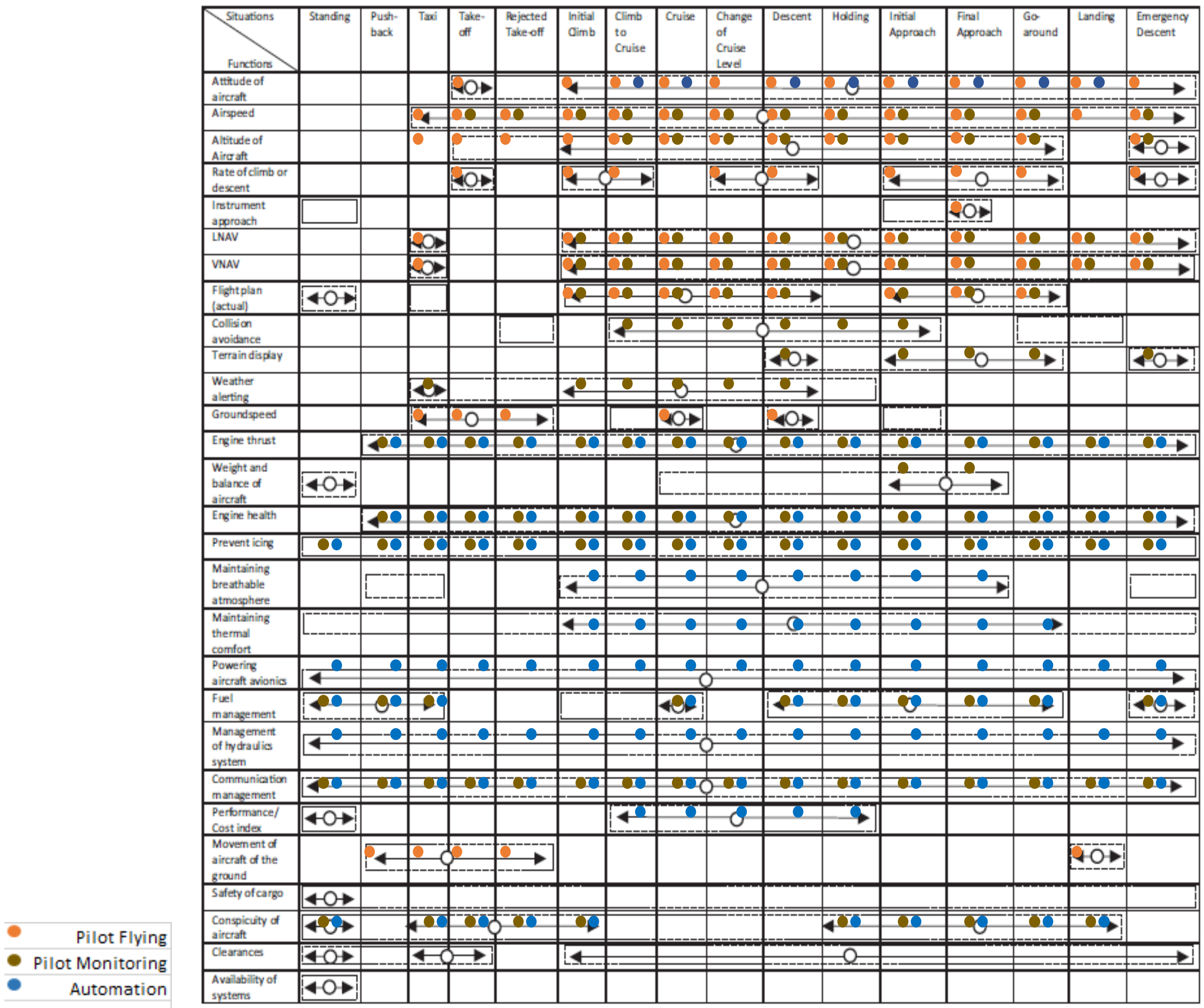
This method builds on Social Organization and Cooperation Analysis Contextual Activity Template [11], which describes the interactions and cooperation among various elements of the sociotechnical system within nominal flight operations. Using this template, the first step is to map out the division of tasks amongst the different actors performing them by placing colored indicators against each function, with each color denoting the roles of actors involved in performing said function. An example is shown in Figure 1. This procedure was repeated for each architecture generated, assigning each task to an actor. Note that the non-colored circle on the table highlights the arrows used to denote the span of situations in which the process is active (using the terms in [11], situations are shown in the columns, often colloquially called phases of flight, and processes are shown in the rows).

Using the measurements from the study of heart rate variance in phases of flight from Ref. [28], this method assigns weights for the notional score of workload in different phases of flight, as compared to today's baseline. To compute a nominal pilot flying workload under each architecture evaluated, the tasks per process for each phase of flight are summed, and then normalized against the number of tasks in today's flight operations. This is a very approximate method to indicate workload, which implicitly assumes that all tasks are equal in workload, and further, assumes that workload grows linearly with the count of parallel tasks, neither of which is operationally true. For example, some tasks may be more susceptible to hypothesis fixation. More detailed methods could include enumerating how many state variables are tracked by the pilot(s) in real time, collecting physiological data to correlate with task performance, or conducting simulator experiments to judge workload. Note that the analysis looks at the predicted increase in workload for a given architecture. The analysis does not take into account the various systems that can mitigate the predicted increase for two reasons. First, this uses a high-level, process-based approach that does not get into specific solutions and their capabilities to manage workload. Second, this approach is somewhat rigidly tied to today's operations model and does not consider the inclusion of completely new processes.

2. Off-nominal Scenarios

When moving to SPO, it is important that the architecture be resilient to the challenges presented by a wide range of off-nominal situations. Because we assumed that today's operations present an acceptable level of safety in off-nominal conditions, when assessing the safety of architectures, this analysis only considered off-nominal conditions unique to single crew operations.

Figure 1 Extended Contextual Activity Template Mapping Processes to Roles [11]. Adapted from Stanton, N. A., Harris, D., and Starr, A. "The Future Flight Deck: Modelling Dual, Single and Distributed Crewing Options." Applied Ergonomics, Vol. 53, 2016, pp. 331–342. https://doi.org/10.1016/j.apergo.2015.06.019.



A unique concern in the move to SPO is the emergence of the pilot as a single point of failure - several possible failure modes of the system as a whole are linked to failures resulting from the actions or condition of the pilot. Pilot incapacitation also makes a few other functions more critical. For example, communications failure (both datalink and voice) becomes more critical. Under today's operations, a communications failure does not necessarily affect safety because current SOPs can accommodate such a failure. In single crew operations, depending on the architecture, a communications failure might imply an immediate diversion. As another example, the failure of an air data computer might decrease speed accuracy below levels acceptable for auto flight.

A second 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. While there are many possible failure combinations given the number of systems in modern aircraft, our model is limited in this regard because it looks at this issue only at a very high level. The scoring for off-nominal scenarios, which is further discussed below, was notional, based on the authors' judgment of the ability of a pilot to handle multiple system failures in a given architecture. For example, an architecture that has a second pilot present in aircraft to perform the duties of the pilot not flying was deemed safer than an architecture that has a ground-based crew member with access to the aircraft systems, which in turn was deemed safer than an architecture with only automation supporting the pilot.

Table 1 lists the off-nominal situations covered in the quick reference handbook used by Airbus A320 pilots [29], identifying the number of checklist actions and memory items, and assigning a severity based on author judgment. Note that Airbus' list of off-nominal situations does not include all tasks that might be encountered - for example, it does not specifically not runway incursions. The severity was graded on a 3 point likert scale, from Low (Monitor and Manage), Medium (Urgent Attention Required), to High (Safety of Flight). The authors' judgment was used to demonstrate the method - both authors are pilots. The lead author has worked professionally as a Human-Machine Interface engineer in aircraft, automotive, and autonomous vehicles, including authoring the pilot operating manual for a Special Light-Sport Aircraft. The second author has worked as an aerospace researcher for 18 years. In future work, it would be desirable to conduct this evaluation across a larger panel of experts, across aircraft designers and pilots.

In evaluating each architecture's ability to deal with combinations of failures, it is evident that systems exist that can prioritize emergency actions into a single checklist [30]. 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. As shown in Table 1, there are at least 18 instances of off-nominal situations where manual flying is necessary. This is not to say, however, that the remaining off-nominal situations are mutually exclusive with manual flight.

Table 1 Off-nominal Situations - Criticality in Phases of Flight and Sum of Actions Required [29]

		Off-nominal condition																																						
	Process Phase	Eng fire on ground	Smoke / toxic fumes	Smoke / avionics smoke	Hyd B + Y Low pressure	Hyd G + B Low pressure	Hyd G + Y Low pressure	Loss of Braking	EGPWS Alerts	TCAS Warning	Engine Dual Failure	Ditching	Emergency Descent	Forced Landing	Cabin Overpressure	Air Dual Bleed Fault	Low Energy Warning	Landing with Flaps/Slats jammed	F/Ctl Rudder Jam	Stabilizer Jam	Gravity Fuel Feed	Fuel Imbalance	Fuel Leak	Double Probe Heat Failure	Display Unit Failure	ECAM Single Display	Ldg Gear Gravity Extension	Ldg with abnormal Ldg Gear	ADR Check Procedure	Unreliable Speed Indication	ADR 1+2+3 Fault	Nav IR Alignment in ATT mode	Engine Relight in Flight	Engine Tailpipe Fire	High Engine Vibration	Overweight Landing	Cockpit Windshield Cracked	Cockpit Windshield Arcing	Volcanic Ash Encounter	Bomb on board
1	Cockpit Preparation			L				L																																H
2	Pushback & Engine Start	L	L	L	L	L	L	L																		L								L	L					H
3	Taxi	L	L	L	L	L	L	M													L		L		L	L								L	L					H
4	Before takeoff	L	L	L	L	L	L	H													L		L		L	L								L	L					H
5	Takeoff	H	M	M	M	M	M		H	H	H	H				L	H		M	M	L		L		L	L			L	M	M	L		M	H		L			H
6	Climb		M	M	M	M	M		H	H	H	H	M	H	L	M	H			M	L		M	L	L	L			L	M	M	L	H	M	H		L		H	H
7	Cruise		H	H	M	M	M		H	H	H	H	H	H	L	M	H			L	M	L	M	L	L	L			M	M	M	L	M	M	M		H	L	M	H
8	Before top of descent		H	H	M	M	M		H	H	H	H	H	H	L	M	H			M	M	L	M	L	L	L			M	M	M	L	M	M	M		H	L	M	H
9	Top of descent		H	H	M	M	M		H	H	H	H	L	H	L	M	H	L		M	M		M	L	L	L			M	M	M	L	M	M	M		H	L	M	H
10	10000 ft/sterile cockpit		M	M	M	M	M		H	H	H	H	L	H	L	L	H	L		M	M		L	L	L	L			L	M	M	L	H	L	M		H		H	H
11	At transition level		M	M	M	M	M		H	H	H	H	L	H		L	H	L		M	M		L	L	L	L			L	M	M	L	H	L	M		M			H
12	Initial approach fix		L	L	M	M	M		H	H	H	H		H		L	H	L	L	M	M		L	L	L	L	H		L	M	M	L	H	L	L		M			H
13	Final approach fix		L	L	M	M	M		H	H	H	H		H		L	H	M	L	M	M		L	L	L	L	H		L	M	M	L		L	L		L			H
14	1000 ft/ 3-4 miles before landing		L	L	M	M	M		H	H	M	H		H		L	H	M	L	M	M		L		L	L	H		L	M	M	L		L	L		L			H
15	Decision height		L	L	M	M	M		H	H	M	H		H		L		M	L	M	M		L		L	L			L	M	M	L		L	L		L			H
16	Landing and rollout	M	L	L	M	M	M	H			M	H		H				M	M	M	L		L		L	L		H						L	L	M	L			H
17	Taxi	M	L	L	L	L	L	H															L											L	L		L			H
18	Park and shutdown	M		L	L	L	L	M															L											L	L					H
	Maximum Number of Actions Taken	7	16	28	1	3	3	7	12	7	19	22	8	26	6	6	1	10	4	5	7	5	9	1	6	4	4	31	3	12	12	8	22	7	5	7	4	1	12	27
	Number of Emergency Actions Taken	3	8	6	0	0	0	3	5	3	4	4	3	3	1	2	1	1	1	1	1	1	3	0	0	0	2	6	2	5	2	0	8	5	1	2	3	0	4	8
	Manual Control Required	Y				Y	Y	Y	Y	Y	Y	Y	Y	Y				Y	Y	Y							Y	Y	Y	Y	Y									

Legend	
High Critical - Safety of Flight	H
Medium Critical - Urgent Attention	M
Low Critical - Monitor / Manage	L

3. *Scoring Architectures for Safety*

The safety score (0-100) consisted of one score for pilot workload (0-50) and one score for the ability to deal with off-nominal scenarios & pilot incapacitation (0-50), with 100 representing current two-pilot operations and 0 representing unsafe. The assessed range varied from 42-74 for the architectures under consideration, as shown in the Results section.

For pilot workload (0-50), the change in workload that the single pilot must take on under nominal conditions for each architecture was evaluated using the detailed process described in Section IV.B.1, with 20 points for takeoff, 20 points for landing, and 10 for cruise operations. As an example calculation, for Architecture A (described in the next Section), the score was computed as (baseline % of workload for pilot flying / new % of workload for pilot flying) * Weighted score for phase of flight. For the architecture (A), this score would be computed as follows. From the Contextual Activity Template, Baseline % of workload for pilot flying for takeoff phase = 17%

Architecture (A) % of workload for pilot flying for for takeoff phase = 52%

Workload score for architecture (A) for takeoff = (0.17 / 0.52) * 20 = 6.5

Scores for for cruise and landing were computed similarly as 4.8 and 10, for a total workload score for Architecture (A) equalling 21.3/50.

The scores for off-nominal scenarios & pilot operations (0-50) were evaluated as 20 points for the ability to deal with the 3 off-nominal corner cases, and 30 points to deal with pilot incapacitation. The three off-nominal combination scenarios, or 'corner cases' were 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. The 20-point off-nominal score was calculated by subjectively assessing how the number of checklist actions for the three scenarios affected the workload for a given architecture. The 30-point pilot incapacitation score was given as follows: full points if a second human were on board (even if not actively involved in flying); fewer points for a remote human, the exact number depending on the anticipated role; and lowest scores for highly automation-reliant architecture.

All score components are presented in Ref. [26], with their combined totals shown in the Results section.

4. Acquisition Costs

The acquisition costs of an SPO aircraft were expected to be more than those of today's two-crew aircraft because aircraft systems for the former will need to be made more reliable, redundant, and robust. To identify such systems, this method expands the sociotechnical model of the flight crew tasks [18] to create a list of systems (see Appendix) that the crew interact with at each phase of flight. This method then quantified the difference in the level of autonomy for each component system under different architectural choices (i.e., replacing the first officer in the baseline model with a ground pilot, on-board automation, or a combination of both) using the hierarchy of automation described by Ref. [31]. For each system moving one level up the hierarchy, this method assumes that the total avionics cost of the aircraft moves up by an arbitrary figure, e.g., 2.5%. A limitation of this analysis is that it does not consider the relative complexity of different systems. All comparisons are 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.

An SPO aircraft will also require new systems to be created [11]. This method uses the expanded sociotechnical model of flight crew tasks to identify phases where new systems may be required, when new players and functions are brought in to replace the F/O. This method assumes that a new system added costs more than a system that needs to be made redundant, which in turn costs more than a system that needs to improve in reliability. A complexity score is then assigned based on the number of new systems added.

5. Operating Costs

In terms of operating costs, the move to SPO offers potential savings in labor costs (Section I). Section III discussed the potential cost savings for two airlines, but airlines will vary in their levels of savings because they differ in their operating contexts, leading to different architectural needs. As discussed in Section III.B.1, additional costs may be incurred in SPO due to the need for new types of crew members and infrastructure.

A baseline model is used to compare operational costs between architectures with the help of a few key assumptions. Costs were calculated on the basis of a notional airline with 300 aircraft, which is a number close to the US average airline fleet size. Twelve pilots per aircraft are assumed for a narrowbody fleet and regional jet fleet, and 10 for a widebody fleet. Average annual pay was assumed to be \$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, respectively, were used. For the number of departures per day, we assumed 4 for narrowbodies, 1.5 for widebodies, and 7 for regional jets. For simplicity, the analysis assumes full fleet utilization and does not take into account spare aircraft or aircraft in down time for maintenance. For ground-based crew members who are effectively pilots, the pay is assumed to be the same as that of an on-board pilot, regardless of the number of aircraft for which they are responsible. This assumption is in line with UAV pilot pay compared to fighter pilot pay scales in the US Air Force [32]. In architectures that require a non-functional pilot to be on board, it is assumed that the non-functional pilot is on half-pay during the time (s)he is on board and not flying.

V. Architectural Decisions

A. Decisions

While the literature describes many SPO architectures at a high level, they have not all been investigated to the same level of granularity. An architecture here is defined as a feasible configuration which answers yes or no for each of these architectural decisions:

- Automation: the duties of the first officer are taken on by additional automation as well improvements to the capabilities of current systems.
- Virtual pilot: defined as the highest form of automation, this decision employs a virtual pilot or avatar fully capable of autonomous flight in emergency situations.

- Ground-based pilot: the first officer is replaced by a ground-based pilot capable of supporting the on-board pilot or flying the aircraft. This decision also includes the option of a super dispatcher who has limited interactions with the aircraft systems.
- Harbor pilot: the ground-based pilot is used only in the terminal stages of flight, similar to how harbor captains guide large ships in and out of busy ports.
- Tag along pilot: a second non-functional pilot travels on board as a backup to the single pilot.
- Wingman: pilots of nearby airborne aircraft provide limited assistance to a single pilot in off-nominal or high-workload conditions.

The scope of the decisions was limited to only single pilot operations and did not explore continuous fully autonomous flight. Full autonomy was explored only as a backup option. Similarly, at the other end of the spectrum, the decisions allowed for two crew members to be present on board but only one operates the aircraft (Tag Along Pilot).

We excluded aspects from the decision space that do not significantly change the architecture, e.g., on-ground screening for medical conditions that may lead to pilot incapacitation, the potential roles played by other crew members like ground staff and flight attendants.

For consistency in the framing of architectural decisions, the decisions used should significantly change the metrics being evaluated [33]. For example, the safety and cost should be significantly different with a tag along pilot vs. without, all else held constant. This test held true for most of the decisions in Section V.A, with the notable exception of the Wingman decision. In the case of this decision, the costs involved were not immediately apparent because the decision of a wingman can range from simple communications support all the way to coordinated procedures that require significant changes in the air traffic system and scheduling. Although the role initially seems to offer limited benefits for SPO, we considered the Wingman decision because it may impact safety when combined with some of the other decisions.

Based on these 6 binary (yes/no) decisions, there are 2^6 possible architectures, not all of which are feasible. The Constraints section (V.B) reduces this space to 14 possible architectures per aircraft type (regional, narrowbody, widebody).

B. Constraints

Table 2 Logical Constraints of the Decision Space

Decision		1	2	3	4	5	6	7
Automation	1							
Virtual Pilot*	2			a	b		c	
Ground Based Dedicated Pilot	3		d		e		f	g
Ground Based Harbor Pilot	4			h				i
Wingman	5							
Tag Along Pilot	6		j	k	l	m		
Super Dispatcher	7							

*UAS autoflight assumed

The architectural decisions listed in Section V.A include some options that constrain each other. Table 2 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 are soft constraints based on logical likelihood. The full list of constraints identified is 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, we can see the following features. First, the Ground-based Dedicated Pilot excludes a lot of the other options, as does the Tag Along Pilot. However, 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 architectures merely change the physical location of the second crew member from the right-hand seat in the flight deck. Second, the Automation decision does not appear to exclude any options because the idea 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. Third, the Virtual Pilot is separately defined as a form of Automation where full autonomous flight capabilities are assumed. This specification is for the sake of simplicity, as the levels of autonomy may fall anywhere on a spectrum with far too many permutations and combinations possible for this analysis. If the aircraft is capable of flying reliably in full autonomy in case the pilot fails, it can be assumed that all ground-based flying roles are redundant.

Finally, there are constraints for roles that are not full-fledged. The Wingman decision does not exclude any other decision because the wingman cannot completely cover the functions of any other role in the other decisions. The Wingman decision, however, is excluded itself by the ground-based dedicated pilot and the tag along pilot because these people can perform better than the wingman, who must manage their own aircraft while assisting any others. Similarly, the duties of a super dispatcher to monitor multiple aircraft under normal conditions limit the amount of interaction with any given aircraft.

When combining these architectural decisions into architectures, it must be kept in mind that the combinations used must replace the first officer's roles and functions in their entirety. Hence, these decisions cannot stand alone: Automation, Virtual Pilot, and Ground-based Dedicated Pilot. Based on these constraints discussed above, Table 3 lists the possible combinations of architectural decisions. Figure 2 illustrates one of these combinations: Automation + Ground-based Dedicated Pilot (AGd).

Table 3 List of Possible Architectural Combinations

Combinations (Denotation)*	
1	Automation (A)
2	Automation + Ground-based Dedicated Pilot (AGd)
3	Automation + Super Dispatcher (AS)
4	Automation + Wingman (AW)
5	Automation + Wingman + Super Dispatcher (AWS)
6	Automation + Tag Along Pilot (AT)

7	Virtual Pilot (V)
8	Virtual Pilot + Tag Along Pilot (VT)
9	Virtual Pilot + Super Dispatcher (VS)
10	Automation + Tag Along Pilot + Super Dispatcher (ATS)
11	Ground-based Dedicated Pilot + Wingman (GdW)
12	Automation + Ground-based Dedicated Pilot + Wingman (AGdW)
13	Automation + Ground-based Harbor Pilot (AGh)
14	Automation + Ground-based Harbor Pilot + Wingman (AGhW)

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

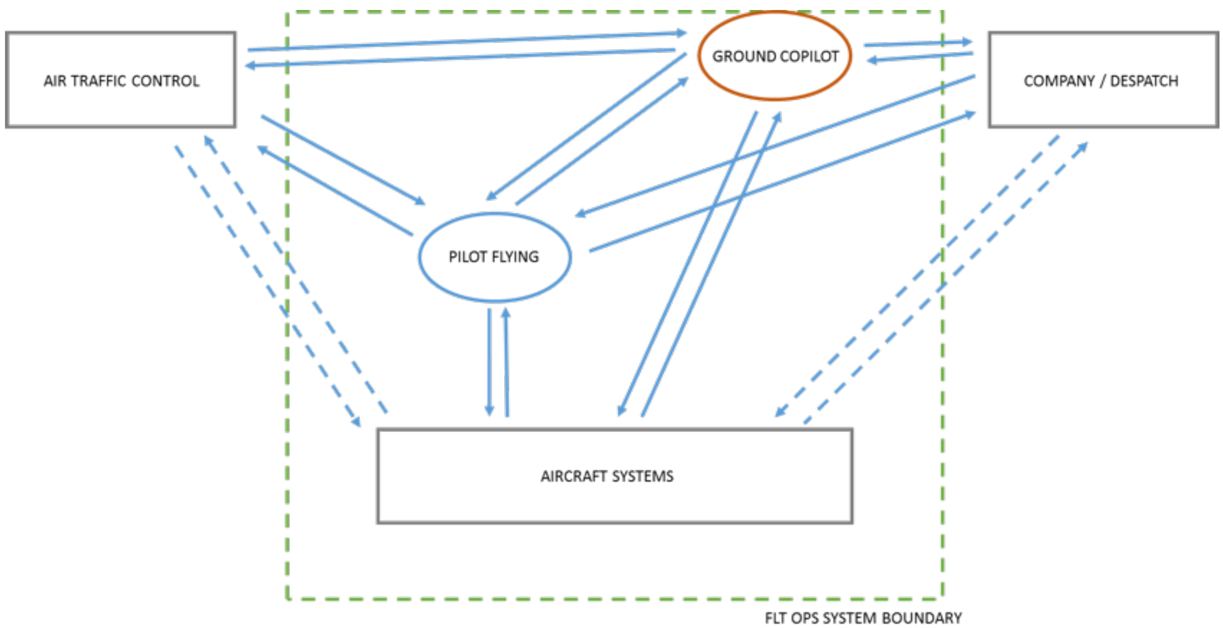


Figure 2 Architecture 2, AGd. Ground co- pilot can communicate with the pilot, ATC, Company Dispatch and Aircraft Systems.

VI. Results

This section presents an exemplar of the method, using the authors' evaluations for the scoring. An example of the nominal operations task assignment was given in Figure 1, which was replicated for each architecture considered.

According to the evaluation of off-nominal operations, 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 pilot flying. 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 remain only with the pilot. We assumed that the number of memory items does not increase in the move to SPO, since the number is currently part of a single pilot's function.

The following sections present the results of this preliminary evaluation as an example of the method, which produces two scores per architecture (safety and cost savings), such that the space of architectures can be plotted on a tradespace. This tradespace can be used to determine which architectures are on the Pareto front, and which architectural decisions are shared between promising architectures.

A. Overall analysis

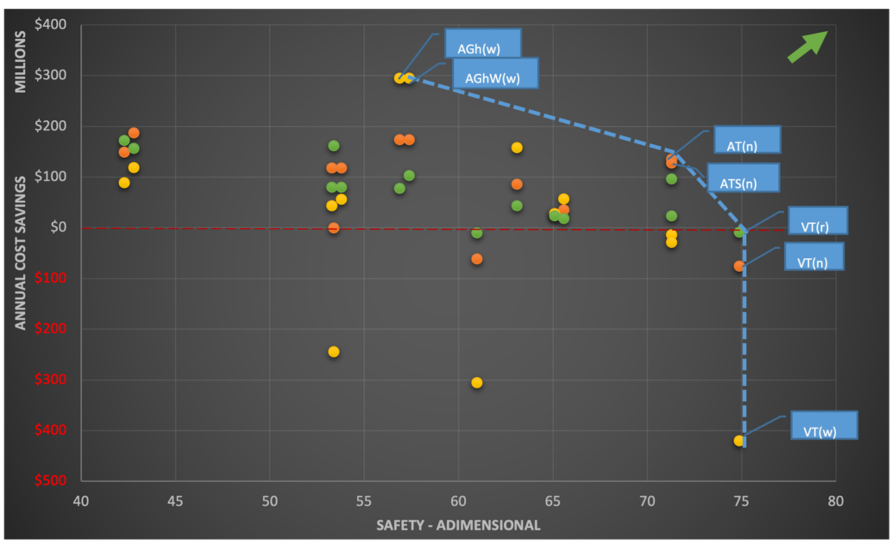


Figure 3Tradespace of SPO Architectures. Aircraft: regional (green), narrowbody (orange), and widebody (yellow). Green arrow points to Utopia point; blue dotted line represents Pareto front.

Figure 3 plots the safety and cost savings scores obtained by comparing the architectures against a baseline formed by today's operations. The tradespace shows that safety and cost are in tension. Architectures with higher inherent safety characteristics are more expensive to operate on an annual basis. A third of the architectures actually incur more costs in operating the aircraft when compared to today's baseline, hence showing negative cost savings.

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 presence of a tag-along pilot. A lot of pairing can also be seen amongst the architectures in the tradespace. These pairings typically consist of architectures that are similar but differentiated by a weakly sensitive decision like the Wingman decision.

The architecture closest in distance to the Utopia point (where safety score and cost savings are at their highest) is Automation + Tag Along (narrowbody) (AT(n)), and the architecture with the highest safety scores is Virtual pilot + Tag Along for all types of aircraft (VT(n), VT(w), and VT(r)). Under current assumptions, however, the VT architecture generates a negative cost savings of $75m. The low cost savings is not surprising: this aircraft has a high ability to deal with off-nominal situations due to the presence of full auto flight capabilities and a backup pilot. While the widebody version of the VT architecture is hugely expensive, the narrowbody and regional jet versions may fall within the margin of error for this analysis. The VT architecture could be brought into the profitable space with different assumptions for aircraft cost, avionics' share of aircraft cost, avionics cost's relationship with complexity, and cost savings in other spheres of operation.

The Tag Along Pilot decision was introduced with the assumption that there would not be much difference in cost savings because the decision retains two fully paid pilots in the flight deck. Interestingly, although AT(n) and VT(n) are conceptually identical, their difference in level of automation appears to drive a huge cost differential while the safety score remains in a comparable range. These results suggest that architectures are more sensitive to acquisition costs than to operational costs.

The architectures with the highest absolute cost savings exemplify another pair: Automation + Ground-based harbor pilot (AGh(w)) and Automation + Ground-based harbor pilot + Wingman (AGhW(w)). Both architectures have identical savings but the architecture 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 to improve cost performance. For example, the absolute savings number is increased by the higher cost of operating widebody aircraft. Further analysis of relative savings is required for a definitive picture.

B. Narrowbody aircraft

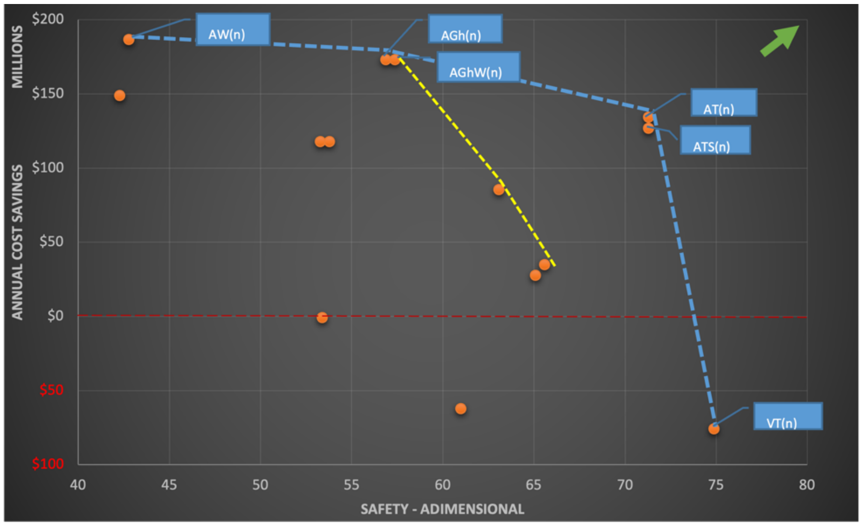


Figure 4Tradespace of Narrowbody Architectures

The narrowbody architecture with the highest savings is Automation + Wingman (narrowbody) (AW(n)), but it also has the second lowest safety score in the tradespace. Further examination of only narrowbody architectures clarifies the higher sensitivity of architectures to acquisition costs compared to operational costs. As can be seen in Fig. 3, the safety scores of AT(n) and VT(n) 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 of the Virtual Pilot.

The Tag Along Pilot decision may be seen as a gateway to enable widespread SPO. The flying community is more likely to accept the decision because two crew members will continue to occupy an aircraft. The Tag Along Pilot decision 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 Pilot architectures are amplified in narrowbody operations because these aircraft typically have more departures per day. Currently, if a two-pilot crew can operate four flights of two hours each, the same crew can operate six flights under the Tag Along Pilot decision 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).

If we eliminate the any architecture containing a tag along pilot from the trade space, then the Ground-based Pilot option falls on the Pareto front (Fig. 3, yellow dotted line). This scenario indicates that the best replacement for the first officer continues to be a human, whether it is a tag along pilot or a remotely located pilot. We can, however, expect many of the architectures to be safer and more profitable—perhaps supplanting the tag along pilot—as capabilities of technology improve, the safety score of automation-centric architectures goes up, and economies of scale kick in from widespread use of SPO technologies.

C. Widebody aircraft

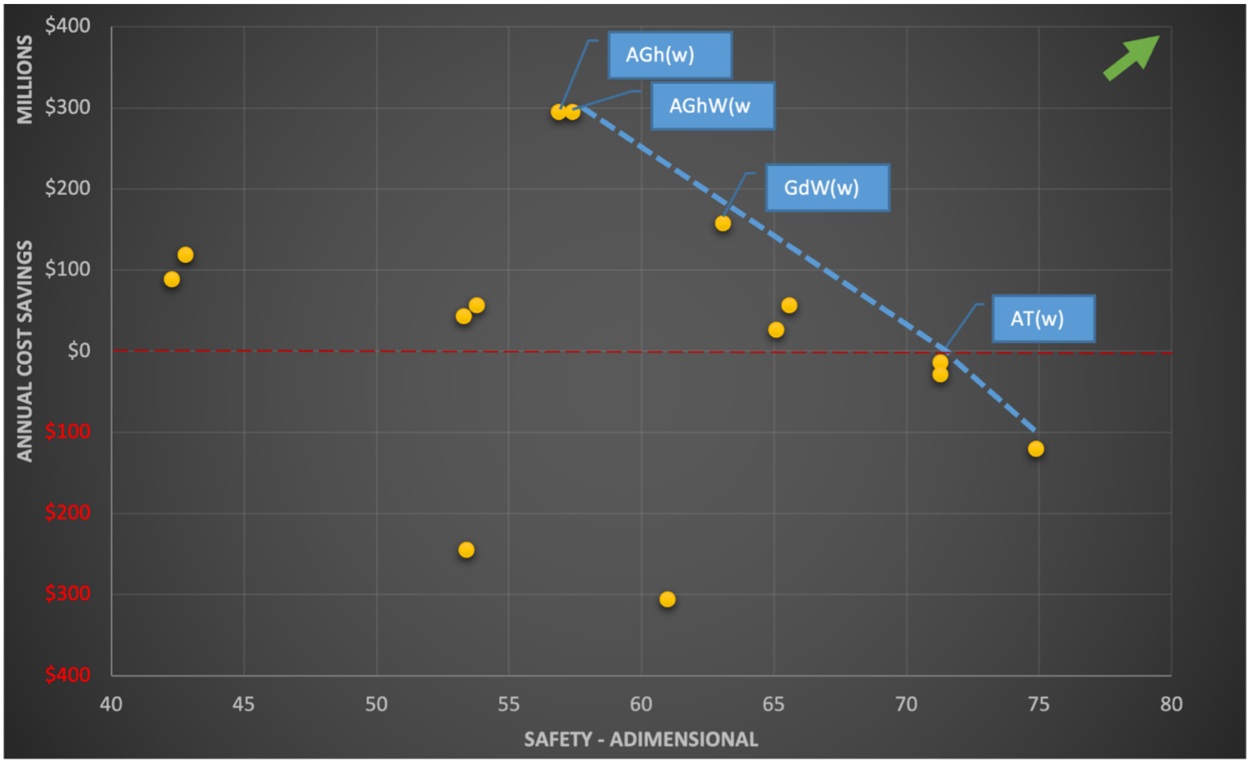


Figure 5Tradespace of Widebody Architectures

When it comes to widebody aircraft (Fig. 4), a greater number of architectures generate negative financial savings compared to narrowbody aircraft. This observation suggests that fleet and crew utilization may be factors that decide the impact of architectural decisions. The safest architecture that generates positive savings is Automation + Ground-based dedicated pilot + Wingman (widebody) (AGdW(w)). The absolute safest widebody architecture is Virtual Pilot + Tag along pilot (widebody) (VT(w)). The negative savings of $120 million are partially due to the fact that crews operate fewer flights. In addition, the higher acquisition cost of the Virtual Pilot decision is not balanced by the savings in operating cost as found with the narrowbodies.

Looking at the tradespace, the Pareto front is not entirely clear. The highest absolute savings are made by the architectures involving harbor pilots, though their safety score is considerably lower than architectures with ground-based dedicated assistance. Improving the safety of harbor pilot architectures may be worthwhile because our analysis of ground-based dedicated assistance did not consider the number of new ground stations (i.e., away from airports) needed to service a long flight. Harbor pilot architectures have a lower safety score because of the limited backup capabilities when the aircraft is out of range of the harbor pilot. The safety score could improve considerably if the autopilot system could be relied upon to keep the plane flying and to hand over the aircraft to the harbor pilot. Such changes may not be expensive compared to enabling systems like full autonomous flight: the industry has decades of experience with autopilots that can handle the cruise phase.

The architecture with the lowest savings is Virtual pilot + Super dispatcher (widebody) (VS(w)). While this architecture may seem superfluous, or ignores a soft constraint, there may be a scenario where the super dispatcher provides strategic support and the virtual pilot provides tactical support. The high cost may be expected, however, given our definition of the virtual pilot (full auto flight system with advanced interaction).

D. Regional aircraft

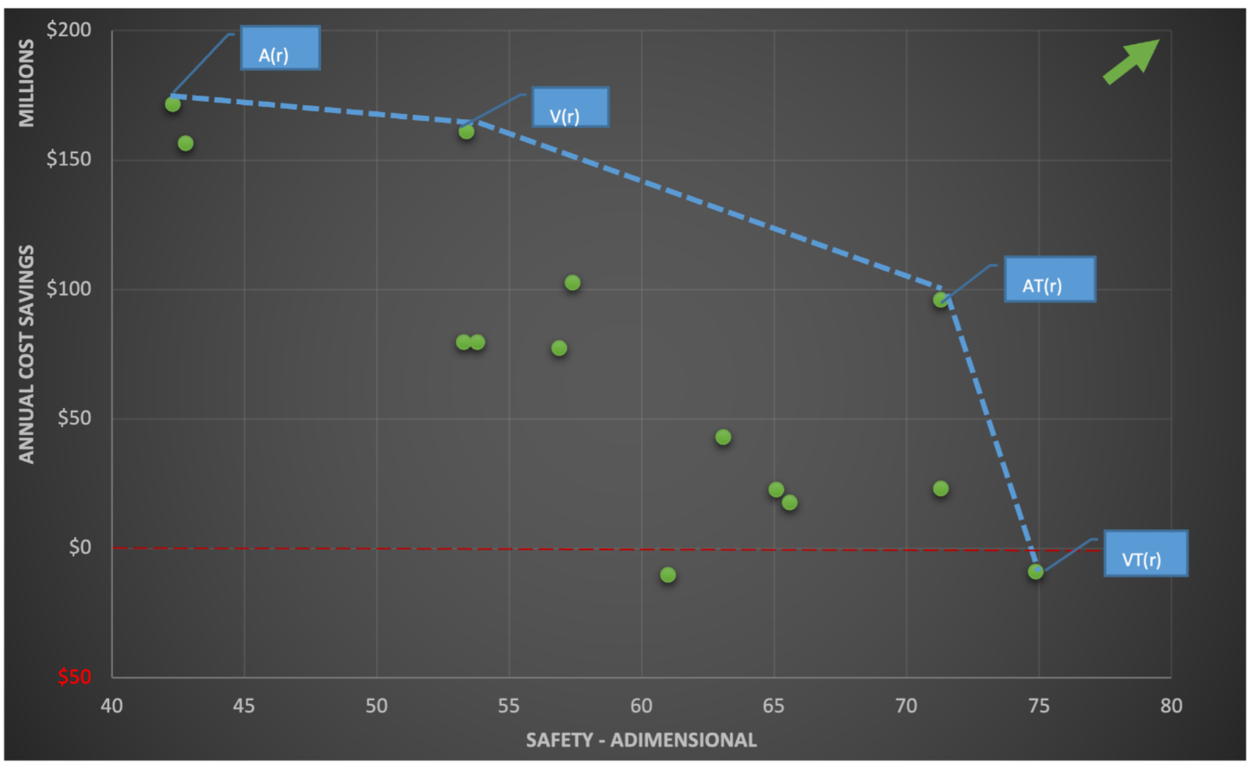


Figure 6Tradespace of Regional Aircraft Architectures

The most interesting results from the analysis lie in the tradespace for regional aircraft (Fig. 5). A majority of the architectures 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 architectures A(r), V(r), AT(r), and VT(r). The first two architectures, which feature 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 greatly increases their safety score. 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 architectures that generate additional costs (i.e., below the dotted red line) are VS(r) and VT(r). The former can be rejected because it has a lower safety score and incurs a higher cost. The latter has the highest safety score and generates an additional cost of only $9 million annually for the notional fleet. This increase may well be mitigated by savings in other components of acquisition cost.

Overall, this method demonstrates 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 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 apply to the same extent as they do for narrowbodies and widebodies. Therefore, safety scores may increase without affecting costs. Since the biggest promise for savings in SPO appears to lie in the regional aircraft space, it should not come as a surprise that Embraer, a manufacturer of regional jets, was the first to announce SPO-capable aircraft.

VII. Conclusions

This paper proposes a method to evaluate new architectures for single pilot operations, according to their safety and cost implications. This method began with two key questions for single pilot operations:

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

To address the first question, safe SPO operations depend on the architectural choices made in enabling SPO. Pilot incapacitation is a particular concern. Architectures that replace the first officer with automation will require capabilities to detect and react to pilot incapacitation scenarios, while architectures that include an extra non-functioning pilot appear to be the most cost-effective means to neutralize pilot incapacitation (Fig. 2). Another issue is pilot workload. This method and the exemplar shown with the authors' evaluations suggests that no architecture scores anywhere close to the current baseline in terms of managing the workload shifting to the pilot flying. This finding is because some decisions must remain 'in the air'. For instance, fuel management can be performed by a pilot assisted by automation, but it would be unwise to hand fuel management completely to a person on the ground. Increasing automation for such decisions may reduce pilot workload, but this solution should be compared against increases in subsystem cost. Finally, for 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. Other architectures that have only one pilot on board fall short because due to the complex nature of aircraft systems, there are failure combinations that can generate a large number of ECAM messages and checklist actions. While modern aircraft systems can compile these actions into a single prioritized list, the actual ability of a single pilot to deal with complex emergencies will largely depend on the design of automated checklist systems. In addition, it is likely that a significant number of checklist actions must be performed by a human, not automation. Therefore, a pilot must be able to perform remaining checklist actions without losing sight of their primary goal of flying the plane, even when they must resort to flying it manually. More efficient human machine interaction can help, through the use of voice, advanced HUDs, and multi-modal interfaces. Such technology, however, comes with a price. Note that this evaluation only considers nominal operations workload, off nominal operations workload, and pilot incapacitation as dimensions of safety, and therefore excludes several other dimensions of safety such as hypothesis fixation.

The second question deals with the financial implications of moving to SPO. This method has the potential to evaluate some of the technology changes required in the process, which could be quite expensive and would add significantly to the ownership costs of a new SPO airplane. Some SPO 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. Some limitations in our analysis include the assumption of notional values for aircraft and the spreading of the total acquisition cost across an assumed 20-year lifespan; our analysis did not consider depreciation and other externalities. In addition, the cost of avionics as a share of the total airframe cost has been increasing as more capabilities are added to the systems on board. At list price with no discounts, a 400-million-dollar A380 costs the same as paying 100 pilots $250k for 16 years, which is shorter than the length of time aircraft are typically kept. From a financial standpoint, the most promising architectures are those that save on capability addition by using a second human either located remotely or on board. However, our tradespace analysis shows that these architectures are more efficient only in the context of short-haul narrowbody operations.

Perhaps the most important research direction stemming from this analysis is the influence of operational context on architectural choices. For example, the Tag Along Pilot decision provides excellent cost savings and extends total crew productivity in a short-haul, high-utilization type scenario. This architecture also emerges as a clear frontrunner in the analysis conducted for regional aircraft, but the decision is far less effective for the long-haul scenario. In the latter scenario, the architecture only makes augmented crew flights more productive, but such flights constitute a very low percentage of total flights under SPO.

A. Areas for Further Study

SPO is a vast and complex subject that will require a lot of effort by academia and industry before it comes to fruition. Because operating context is an important factor in choosing SPO architectures, a key focus for the future is the business impact of SPO. We need to identify the benefits and shortcomings of SPO for various types of operators —passenger airlines, cargo operators, regional airlines, special mission operators—as well as the potential for architectural commonality and modularity to address their needs. A second area of focus is the relationship between SPO and the pilot, e.g., the effect of increased workload (especially under off-nominal conditions) and incapacitation (and how to prevent it), which in particular would benefit from a broader panel of experts using this method to evaluate pilot workload. The impact of SPO on pilot shortages should also be examined as fewer people choose flying as a profession due to expensive initial training and low entry-level remuneration. Third, while this paper made high-level architectural comparisons for SPO, examining the systems with greater detail would allow us to better identify the precise capabilities of each architecture, and better predict their ability to deal with off-nominal situations and corner cases. Finally, research is required into the moral and ethical questions around SPO. Similar to autonomous cars, the degree and hierarchy of control for SPO aircraft, as well as permissions for actions, need to be carefully considered, especially for scenarios in which a person who is not on board the aircraft is placed in charge of the lives of scores of people far away from them.

E. Appendix

Table 4 List of systems that the crew interact with at each phase of flight

Process phase	Process subphase		Process Gate	Flight Crew Communication	Flight Crew Decisions & Actions*	Captain Systems Inteaction	F/O Systems Inteaction	Level of Automation
Preflight	Flight planning and briefing	1	Crew arrives	Scheduling				
		2	Dispatch	Dispatcher	Review/accept	Desktop s/w, wx, flt pln, wt & bal	Desktop s/w, wx, flt pln, wt & bal	
		3	Crew meeting					
		4	Transfer to aircraft					
	Aircraft release and turnaround	5	Arrive at aircraft	Gate staff				
		6	Aircraft status/Status of process Aircraft ready - technical register of airplane	Maintenance, Ramp	Safety check		External visual integrity	MC
		7	Full crew briefing	Cabin Crew				
		8	Cabin ready to board	Cabin Crew	Cockpit prep, checklists (48)	Electrics, APU, Hydraulics, FMC (Air data, Nav, FPlan), Cabin environment, ECAM (Fuel, Doors, Flt Controls), Xpdr, Comms (radio, intercom)		
		9	All doors closed	Cabin Crew			CL support for same systems.	MC, AS
Flight execution	Push back / engine start	10	Out of gate/off blocks	ATC Ramp	Engine start CL (15)	APU, Electrics, ECAM (fuel, doors), Engines	Radio comms, CL support for capt systems	AS
	Taxi	11	Taxi	ATC Ground	Pre-departure CL (17)	Electrics, Hydraulics, Brakes, ECAM, APU, Flt Controls	Radio comms, CL support for capt systems	AS
	Takeoff	12	Ready for takeoff	ATC Tower	Before TO CL (7), Callouts, TO decision	Brakes, Electrics, Engines, Xpdr (TCAS)	Radio comms, SOP callouts & actions, CL support for capt systems	AS
	Climb	13	Climb	ATC Departure	After takeoff CL (8)	Engines, Hydraulics, Electrics, Autopilot (LNAV, VNAV)	Radio comms, CL support for capt systems	AS, ADM after autopilot engaged
	Cruise	14	Cruise	ATC Enroute		Autopilot inputs, ACARS (route amendment, company comms), Wx Radar	Radio comms, FMC programming, monitor automation	SC
	Descent, approach and landing	15	Before top of descent		Automation interactions	Electrics, Nav, FMC programming	Radio comms, FMC cross check, CL support	SC
		16	Top of descent					SC
		17	15 minutes before landing					BDM
		18	10000 ft/sterile cockpit	ATC Approach	Briefing, Before landing CL (16)	Cabin environment, FMC (Nav), Electrics, Hydraulics		BDM
		19	At transition level				Radio comms, CL support, SOP actions	BDM
		20	Initial approach fix					BDM
		21	Final approach fix					BDM
		22	1000 ft/ 3-4 miles before landing		Autoland decision			BDM on autoland, DS otherwise
		23	Decision height	ATC Tower	Callouts	Hydraulics, FMC (Alt), Electrics	Radio comms, CL support, SOP actions	BDM on autoland, DS otherwise
		24	Landing and rollout					BDM on autoland, DS otherwise
	Taxi	25	Taxi	ATC Ground	After landing CL (8)	Hydraulics, Engines, Xpdr, Electrics, Brakes, APU	Radio comms, CL support, SOP actions	AS
	Park and shutdown	26	Park and shutdown	ATC Ramp	Parking CL (7), Securing aircraft CL (9)	Brakes, Engines, Electrics, ECAM (Fuel), FMC (Air Data, Nav), APU	Radio comms, CL support	AS
Postflight	Flight report	27	Flight report	Maintenance	Safety, Maintenance report decision			
	Change aircraft/prepare for next flight	28	Change aircraft/prepare for next flight	Scheduling				

* - 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.

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