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SURVEY PAPER

Single-pilot airline operations: Designing the aircraft may be the easy part

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Abstract

For financial and operational reasons many aircraft manufacturers are working on the development of single-pilot commercial aircraft. It is suggested that cargo operations may commence in the early 2030s followed by passenger flights later that decade. Two technological approaches for the development of single-pilot airliners are being developed either based upon extant technology and operating concepts derived from uninhabited aviation systems and military aircraft, or alternatively based upon high levels of onboard autonomy/automation. This review considers the economic, technological, regulatory (safety) and societal acceptance of the single-pilot airliner, and examines some of the operational challenges that airlines may face. It is suggested that while the technological and safety challenges may be resolved, it is the operational challenges that may determine if the concept is ultimately viable.

Nomenclature

ACARE	Advisory Council for Aviation Research and Innovation in Europe
ACROSS	Advanced Cockpit for the Reduction of Stress and Workload
AI	Artificial Intelligence
ALPA	Air Line Pilots Association
ANO	Air Navigation Order
AOC	Air Operator’s Certificate
AOCCs	Airline Operations Control Centres
ATI	Aerospace Technology Institute
ATPL	Airline Transport Pilot’s Licence
ATSB	Australian Transport Safety Bureau
CAMA	Cockpit Assistant Military Aircraft
CAMMI	Cognitive Adaptive Man-Machine Interface
CASSY	Cockpit Assistant System
CFR	Code of Federal Regulations
COGPIT	COGnitive cockPIT
CRM	Crew Resource Management
CS	Certification Specification
EASA	European Aviation Safety Agency
ECA	European Cockpit Association
eMCO	Extended Minimum-Crew Operations
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IMC	Instrument Meteorological Conditions

MCAS	Maneuvring Characteristics Augmentation System
NASA	National Aeronautics and Space Administration
SiPO	Single-Pilot Operations
SOP	Standard Operating Procedure
UAS	Uninhabited/Unmanned Aviation System

1.0 Introduction

International regulations for the carriage of air passengers dictate that two pilots are the minimum flight crew complement for a large commercial aircraft. In Europe, any aircraft that is operated on an AOC (Air Operator's Certificate) with turbine power, cabin pressurisation and/or under Instrument Flight Rules (IFR) must be piloted with a minimum of two flight deck crew. Article 25(3) of the UK Air Navigation Order [1] states:

> *A flying machine registered in the United Kingdom and flying for the purpose of public transport having a maximum total weight authorised exceeding 5,700kg shall carry at least two pilots as members of the flight crew.*

Furthermore, the ANO is a legislative (as opposed to regulatory) requirement.

Nevertheless, this may change. As part of the FAA Reauthorization Act 2018 [2] it was stated that the '*Administrator shall transmit a report to the Committee on Science, Space, and Technology of the House of Representatives and the Committee on Commerce, Science, and Transportation of the Senate that describes... a review of FAA research and development activities in support of single-piloted cargo aircraft assisted with remote piloting and computer piloting*'. Such a change in legislation would clear the way for the introduction of a large, single-pilot passenger aircraft. In January 2021, FlightGlobal reported that EASA (European Aviation Safety Agency) was also considering relaxing the rules and allowing single-pilot operations in commercial aviation [3]. In 2021 EASA commissioned a review and research into extended minimum crew and single-pilot operations for large, commercial aircraft with the objective of producing a safety risk assessment framework [4].

Most major aircraft manufacturers and avionics systems suppliers are working on the development of single-pilot aircraft. Embraer has stated that they will provide single-pilot capability by 2025. Airbus has openly stated that they are developing technologies that will allow a single pilot to fly an airliner and has suggested that the newly launched A350 Freighter is a potential candidate for single-pilot operations (SiPO). Boeing has undertaken initial experimental flights where autonomous systems made some of the pilot's decisions. There has been speculation in the aviation press that the planned Boeing 797 may be capable of single-pilot operations [5]; however, in response Boeing Research and Technology vice-president Charles Toups commented that SiPO operations would most likely commence with cargo flights, and it would be a 'couple of decades' before passengers would be prepared to fly on them.

NASA (National Aeronautics and Space Administration) has been undertaking a major research programme investigating technology and operational options for single-pilot aircraft (see https://eurasiantimes.com/nasas-passenger-airplanes-might-just-have-one-single-pilot/ [6]). In the UK, work is also being undertaken as part of the ATI (Aerospace Technology Institute) funded Future Flight Deck and Open Flight Deck programmes to determine the technology requirements and crewing strategies for a single-crew airliner. The ATI technology roadmap anticipates single-pilot cargo aircraft being introduce by the end of the 2020s and airliners in around 2035 [7].

EASA defines two categories of commercial flight using a single pilot. Extended Minimum-Crew Operations (eMCO) will be based upon development of extant designs where single-pilot operations will be restricted to the cruise phase of flight (e.g. the European ACROSS project: Advanced Cockpit for the Reduction of Stress and Workload (see https://cordis.europa.eu/project/id/314501). These will likely be implemented on long-haul, trans-continental flights. Under eMCO only one pilot will be required to remain on the flight deck during large parts of the cruise phase while the other pilot (who may still be the designated pilot in command) rests in a crew area outside the flight deck. Under SiPO there will only be one pilot onboard at any time, from take-off until landing.

Flight deck configurations and operating concepts for eMCO and SiPO will be quite different in nature. SiPO aircraft will be specifically designed for operation by one pilot during all phases of flight. Furthermore, flight durations are likely to be much shorter, restricted to intra-continental and regional operations, but may include operations into and out of less-well-equipped, regional airports as well as major hubs.

eMCO and SiPO aircraft will receive support from the ground, both during routine normal operations (e.g. during take-off and approach and landing) and non-normal/emergency operations. However, the amount and nature of this support is likely to be quite different, particularly in the degree of control exerted over the aircraft and its systems. eMCO aircraft are likely to receive operational support from personnel embedded in AOCCs (Airline Operations Control Centres). This may be technical support derived from the monitoring of aircraft systems, or navigation/routing/passenger-handling support, etc. (as based on current practice). However, direct control over aircraft systems is unlikely. In SiPO aircraft, higher levels of onboard automation/autonomy will be implemented, but direct control will also be available from ground-based support personnel. However, this will depend upon the system architecture underlying individual design’s operational concept. This discussion is restricted to the technologically and operationally more challenging SiPO concept.

Harris [8] described five major requirements for any SiPO airliner. The aircraft must:

- Be capable of operating in all types of current (and envisaged) airspace without special ATC/ATM procedures and operate in weather the same as current airliners: compatible with current multi-crew aircraft operating in the same airspace.
- Be able to be flown by Airline Transport Pilots Licence (ATPL) qualified professional pilots without extraordinary training (but will require training specific to single-pilot operations, e.g. adaptations of crew resource management – CRM – practices).
- Be capable of being operated into major international hubs in complex, busy airspace but also be capable of operating into remote airfields with limited ATC cover and only basic landing aids (to help increase access to the air transportation system – see ACARE FlightPath 2050 goals [9]).
- Have lower *overall* operating costs than that of a multi-crew aircraft, which includes all acquisition costs, training, maintenance and operational support.
- Exhibit *at least* an equivalent level of safety to fourth-generation modern airliners in all respects.

Furthermore, Harris [10] argued that the Human Factors requirements will be the prime driver for the design and development of SiPO, not the hardware and software technologies. Pilot unions also have operational and safety-related concerns, which will pose challenges for such a new air transport system [11–13].

It is argued that while the development of the required technology will be challenging, there is an extensive extant engineering basis from which to proceed. The greatest obstacles to the introduction of a single-pilot aircraft are the Human Factors requirements, operational and organisational challenges, and the new concepts of operations required to make such an aeroplane safe and useable in airline service.

Adopting a commercial perspective, the Boeing Airplane Company identified four areas that need to be satisfied before a new aerospace product will be accepted for use: economic considerations; the technology; regulatory (safety) aspects; and the societal acceptance of the concept. However, for the single-pilot airliner a fifth attribute also needs to be addressed: the organisational aspects of the operation of such an aircraft in airline service. There is a great deal of overlap between these areas: training cannot be separated from safety, nor can the technology or regulation. Furthermore, there is no point in designing a technologically advanced aircraft if it cannot be operated in a commercial context, which is the whole point. These divisions are by no means meant to be definitive nor mutually exclusive.

2.0 Rationale for single-pilot commercial aircraft

2.1 Original impetus for single-pilot operations: Economic considerations

The original rationale for single-pilot operations was to reduce operating costs. However, Human Factors is not a cost: it can significantly contribute to improvements in operational efficiency [14]. Flight crew costs can represent up to 15.3% of operating costs depending upon aircraft type, sector length and how much activity is outsourced [15–17]. The pilots themselves represent almost 7% of operating costs. The airline industry is not a particularly profitable one: there are constant downward demands on pricing and unpredictable, fluctuating fuel costs coupled with a low operating margin. Over a decade ago, it was estimated that on a global basis, between 2000 and 2010 the aviation industry lost $47 billion [18]. Pre-COVID, the International Air Transport Association (IATA) reported globally that post tax profits declined from $9.13 (per passenger) in 2016, to $7.69 the following year [19]. At the height of the COVID-19 pandemic, 2020 post-tax losses (per seat) in North America were $35.1 and in Europe were $34.5 [20]. As a result, IATA estimated that worldwide, airlines recorded a net loss of $126 billion in 2020, followed by a further $48 billion in the following year.

For US major inter-continental airlines each aircraft requires (on average) 12.55 pilots; US national airlines require 10.15 pilots per aircraft; US regional airlines, flying smaller aircraft require around 8.17. The annual financial reports of a major European low-cost operator suggest that each aircraft requires between 9 and 10 pilots, with the proportion of Captains and First Officers in the company marginally favouring the former [15]. Using the Boeing 737-300 as a baseline, it has been estimated that over a 25-year operational life, a single-pilot airliner would save between $1.25 and $4.38 million per aircraft [21].

Parimal Kopardekar, concepts and technology development project manager at NASA Ames Research Center, noted that if single-pilot operations became commonplace, rather than threatening jobs (a concern for many pilot's unions), it may have the opposite effect: The cost per passenger seat mile would decrease. ALPA themselves [11] estimate that removing one of the flight crew would cut around 4% from the total cost of a flight; Moehle and Clauss [22] assess the corresponding saving to be 2–3%. As a result of such economies, ticket prices would fall, yielding an increase in demand potentially requiring more pilots. A move to single-pilot operations could yield a growth in revenue, passenger numbers and an increase in feasible routes while simultaneously resulting in an unchanged demand (or an increase) in the number of pilots [23].

Other factors have now accelerated the need for the development of single crew airliners. Airbus anticipates that approximately 39,000 new aircraft will be required in the next 18 years, nearly doubling the current fleet size [24]. The corresponding Boeing estimate is even higher suggesting a demand for over 47,000 aircraft by 2041 [25]. However, commensurate with the increase in demand there is also an accelerating, global shortage of airline pilots. Estimates vary: In the US it is projected that there will be a shortage of 35,000–40,000 pilots by 2035 [26, 27], the majority of which will be borne by the regional carriers. Boeing expect that between 2021 and 2040, the world's airlines will need 612,000 new pilots [28]: 130,000 new pilots will be required in North America: 115,000 in Europe and 250,000 in the China/Asia-Pacific region. Over 60% of these pilots will be needed to service airline expansion. FAA regulations, including changes in the required durations of rest between flights and the revised minimum flight experience for new hires have also contributed to this shortage [29].

Tackling such shortfalls has usually been regarded as a recruitment and training issue. However, single-pilot, short-range airliners will provide a further option for reducing costs and the potential shortage of pilots. Furthermore, single-pilot aircraft will also provide greater flexibility in crew rostering [30, 31], as issues in the appropriate pairing of crews will no longer be relevant, hence will also further reduce the size of the pilot pool required by an airline to satisfy crewing requirements (pairing Captains with appropriately qualified First Officers).

Nevertheless, any single-pilot airliner will require more personnel on the ground to support it. As will be discussed later, the size and functions of this ground support will depend upon the technological approach being employed. If a single-pilot aircraft is to result in significant cost savings, the ratio of personnel involved in the ground support component to those on the flight deck needs to be less than the current 1:1 ratio of First Officers to Captains. This will be a considerable challenge.

2.2 New opportunities

Recently a third rationale for the introduction of single-pilot regional operations has emerged. Short-range, electric commercial aircraft are being developed (e.g., the 19-seater Heart Aerospace ES-19, currently scheduled for service entry in 2026). Although the operating costs of such aircraft are anticipated to be considerably lower that their equivalent fossil-fuel powered contemporaries (anticipated fuel costs will be 50–75% of equivalent aircraft and maintenance costs 50% lower), the operating economics of such aircraft would benefit greatly from a reduction in flight deck crew, as currently the cost of two pilots must be amortised over just 19 seats. Significant weight reductions are also possible, especially if the flight deck is re-designed to accommodate a single pilot, relieving the aircraft of not only the weight of the pilot but also their seat, displays and associated controls, while simultaneously simplifying systems. In such an aircraft, this weight saving may translate into additional passengers/payload, extra batteries for greater range, or enhanced performance.

3.0 Technological approaches for a single-pilot airliner

One of the greatest challenges is concerned with designing the flight deck for the envisaged end user (i.e. the pilot). The Human Factors requirements for the SiPO aircraft will (by definition) be the prime design driver, determining the functions of the supporting hardware and software technologies [10]. One pilot must do the job currently undertaken by two. SAE International ARP 5,056 asserts that the end-user pilots should be central to the design process [32]. It specifies that the characteristics of the target pilot population should be determined and include considerations of anthropometry; culture (national, corporate and operating environment) and language, and that the design should also take into account the variability in piloting skill in the likely population of pilots operating the aircraft. The UK Ministry of Defence goes further and suggests the description of the end user group should also specify any particular aptitudes and abilities; reasoning and/or decision-making skills and other specific skills and qualifications [33]. Historically, smaller regional airliners are often piloted by younger, more inexperienced pilots, especially in the First Officer role, but for SiPO aircraft all pilots must be Captains, hence may require more experienced pilots. Defining the target pilot for the single-pilot airliner will be a crucial first step.

Two distinct technological approaches underpin the development of single-pilot airliners [34, 35]. One concept is based upon onboard high levels of automation, for example, intelligent knowledge-based systems, autonomous systems and adaptive automation. The alternative approach is more technologically cautious, using a design philosophy based upon existing technology and operating concepts derived from UASs (Uninhabited/Unmanned Aviation Systems) and single-seater military aircraft, which displaces the second crew member to a ground station. These approaches should not be characterised as ‘either/or’ options: they share technology and operational challenges. They are better characterised as ends of a continuum. Even the highly automated/autonomous approach will still require ground support.

The early design approaches for a single-pilot aircraft utilised a great deal of onboard technology. The emphasis was on adaptive automation and decision aids in the form of ‘intelligent co-pilots’ or ‘cockpit assistants’ (e.g. COGnitive cockPIT – COGPIT programme [36]; Cockpit Assistant Military Aircraft – CAMA programme [37]; Cockpit ASsistant SYstem – CASSY [38]). These systems monitored pilot inputs comparing them against data from the status of the onboard systems (for example, position of the aeroplane and external environmental factors) using algorithms to determine if there was any significant difference between the actual and expected states [39]. Studies for developing concepts for single crew operations were also predicated upon incorporating extensive automated (deterministic) control and procedural assistance on the flight deck, defining the automated support required [40, 41].

These earlier systems were of limited success, largely as a result of the computing technology available in the 1990s. Such systems were best characterised as ‘highly automated’ rather than possessing any degree of autonomy. The slightly later CAMMI (Cognitive Adaptive Man-Machine Interface) project used extensive AI software to support the adaptive automation installed in the aircraft [42]. The software was not used to control the aircraft directly: it had four goals:

- Task scheduling (e.g. direct the pilot to higher priority tasks; defer lower priority tasks and/or assist pilot in task-switching)
- Modify pilot interactions with the system (e.g. de-clutter displays; highlight important information or change the modality of incoming information)
- Task off-loading (e.g. automate lower priority tasks); and
- Task sharing (e.g. provide automated assistance to simplify the tasks)

However, many autonomous systems are now being developed for numerous applications including the direct control of driverless cars, UASs and planetary landers. Recent advances in autonomous technology make this technology increasingly viable for the development of a single-pilot airliner.

Where automation ends and autonomy begins is a moot point. UK MoD Joint Doctrine Notice (JDN 3/10) [43] defines an autonomous system as being "*. . .capable of understanding higher level intent and direction. From this understanding and its perception of its environment, such a system is able to take appropriate action to bring about a desired state. It is capable of deciding a course of action, from a number of alternatives, without depending on human oversight and control, although these may still be present. Although the overall activity of an autonomous unmanned aircraft will be predictable, individual actions may not be*". In contrast, automation comprises sets of tasks, which may be extensive, complex and branching and requiring little operator input once initiated. These are well-defined, rule-based tasks with predetermined responses. Automated systems are only minimally responsive to the operating context, responding to pre-defined events. Autonomous systems incorporate AI and have adaptive capabilities allowing them to respond (within predetermined bounds) to situations which have not been anticipated and hence not pre-programmed. They have a degree of self-governance and self-directed behaviour, which adapts to the context and learns. Unlike automation, an autonomous system may exhibit emergent behaviour, utilising feedback to learn and adapt. As a result, such systems may respond differently at a later instance when faced with identical inputs.

A variable (or semi-) autonomous system adjusts the levels of authority it possesses as determined either by the human operators (pilots) or the context of operation. At a low level, autonomous systems may assist the pilot by advising on issues such as flight profile optimisation or provide system management [42]. It may also support the pilot by anticipating and preventing some critical situations (e.g. fuel starvation or icing). In the case of an imminent accident detected by an on-board collision avoidance system the autonomy may have delegated authority for engaging in emergency manoeuvres where the single pilot is incapacitated or is unable respond in time [44]. This encapsulates the nature of 'scalable autonomy'. It is likely that any autonomy implemented in a single-pilot airliner will be such a system.

In contrast to the extensive use of on-board automation/autonomy, a distributed crewing design philosophy utilises extant technology derived from single-seater military aircraft and UASs (including ground station design). This approach has been adopted by the UK Future-Flight Deck and Open Flight Deck programmes [10, 45, 46] and by NASA in its single-crew commercial aircraft design concept [47]. This design philosophy considers the single-crew aircraft to be part of a wider system. The high-level system architecture underpinning the operation of such an aircraft consists of several discrete elements, comprising the aircraft itself (including pilot) and a ground-based component staffed by a 'Second Pilot'/'Ground Pilot' support station/'Super Dispatcher'/'Harbour Pilot' (see following section); real-time engineering support and a navigation/flight planning support facility. With this approach, the second pilot is not directly replaced by on-board automation or autonomy; they are displaced. This philosophy is also commensurate with many operating concepts in major airlines, where aircraft are supported by staff in an AOCC whose functions include scheduling of aircraft; real time monitoring of engineering data (often with embedded engineers from aircraft and engine manufacturers); support for in-flight re-routing and coordination of ground-based resources.

To ensure safe and efficient flight there must be an appropriate allocation of work between personnel (both pilots in the aircraft and operatives in ground-support roles) and automation. For both technological approaches, the development of sophisticated automation and/or autonomy is necessary to reduce the demands on the pilot in times of high workload or to take control in the case of incapacitation. Intelligent systems are being developed for the dynamic allocation of workload based upon physiological parameters, cognitive indicators, operational and environmental conditions, system and interface variables [48–51]. When the onboard pilot monitoring systems detect a crew member is becoming overloaded, these systems re-distribute tasks to ground support and/or the onboard automation. Several methods for investigating the design options for the allocation of functions in these circumstances have been utilised [40, 46, 48, 52, 53] most of which have been based upon cognitive task analytical approaches. Analyses suggest that many of the second pilot's tasks, especially those associated with cross-checking, surveillance and monitoring, can be re-distributed to on-board automated/autonomous systems. However, higher-level decision-support will depend upon the design approach adopted (see following discussion). In the distributed crewing option, decision-support functions will be provided by ground-based personnel (second pilot, engineering, navigation or meteorology support functions). In the case of the single crew airliner incorporating higher levels of autonomy these functions are likely to be undertaken by on-board AI systems. In high workload, off-nominal situations or emergencies, increased authority and responsibility can be delegated to the autonomous systems (e.g. in the form of partially pre-scripted playbooks for the re-allocation of functions) relieving the workload on the pilot. These 'plays', based upon task models derived from the flight situation, standard operating procedures and checklists, can be modified at the behest of the pilot [54].

Nevertheless, the highly automate/autonomous and the distributed crewing approaches can be complementary. The distributed crewing approach can provide a platform for development of the (semi-) autonomous systems required for later, more technologically advanced versions of the aircraft and begin to develop operating concepts.

3.1 High level system architectures

In addition to the degree of automation/autonomy on board the single-pilot airliner, there are also higher-level considerations relating to the wider system architecture. These also impinge directly on the aircraft operating concept and the operational challenges faced by the single-pilot airliner system.

In NASA's Single-Pilot Operations Technical Interchange Meeting [23] five basic configurations were discussed by participants. The option where a single pilot assumed the duties of the second pilot flying current technology aircraft was included as a baseline configuration; however, this option is now under active consideration for cruise phases of flight in the EASA eMCO concept of operation. Four other system configuration options were discussed:

- **Single pilot with automation replacing the second pilot:** Similar in concept to the early approaches for the development of a single-pilot aircraft, which mostly utilised onboard technology in the form of 'intelligent co-pilots' or 'cockpit assistants'. However, more capable automated/autonomous systems can now potentially be employed to this end. Even so, there will still remain a need for remote support of a single-piloted aircraft [55, 56].
- **Single pilot with a ground-based team member replacing the second pilot:** Neis, Klingauf and Schiefele [34] described four broad sub-categories of configuration using this approach:
    - **Remote Pilot:** This is the simplest concept. In this case the ground-based pilot has the capability of exerting control of the aircraft, supplementing or replacing the on-board pilot if required [57]. They are available to the pilot at any point during the flight (including pre-flight and shut down) and operate on a 1:1 basis (when needed) with the aircraft, but normally, the aircraft operates only under the control of the on-board pilot. A high degree of on-board automation will still be required in this configuration [53].
    - **Harbour Pilot:** This is similar in concept to its marine equivalent. The Harbour Pilot possesses knowledge of a well-defined terminal area airspace, its procedures and operations, and provides real-time support to the single pilot during departures and arrivals [47, 57, 58]. They may take control of the aircraft, if required. Schmid and Korn [59, 60] proposed an architecture

    combining aspects of both the Remote Pilot and the Harbour Pilot concepts, where three separate ground-based operators are employed for support during departure, enroute and arrivals.
  - **Hybrid Ground Operator**: This ground-based operator undertakes dispatch and support to multiple nominal aircraft but provides dedicated 1:1 support to any aircraft during a non-normal or emergency situation. In this case, other aircraft being supported will be transferred to another operative. This SiPO concept was promoted in a number of simulation studies undertaken by NASA [47, 61]. The 1:1 remote pilot configuration was evaluated in simulated in-flight diversion and emergency scenarios in the NASA SPO II trials [62]. These trials also involved several prototype collaboration tools to enhance pilot/ground-station communication and coordination. The analysis showed that it was feasible to manage successfully all the scenarios undertaken using a remote pilot.
  - **Specialist Ground Operator:** These fall into two further sub-categories – Ground Associates, who undertake normal dispatch and pilot support activities ('Super Dispatchers' [63], and Ground Pilots who remain on stand-by to take over support during any non-normal or emergency situation. This could be further extended (the 'Apollo 13 scenario') where the Ground Pilot calls upon the collective expertise of other members of the distributed team in the AOCC (real time engineering support, support for in-flight re-routing, passenger handling and logistics, etc.).
- **Single pilot with onboard personnel serving as a back-up pilot:** This option made provision for other personnel on the aircraft; for example cabin crew, to serve as an emergency second pilot but subsequently as not considered to be a viable development route [23, 34].

All the above categories pose different research and development challenges and have operational and technical advantages and disadvantages. However, they have common underlying questions determining the viability of the single-crew concept. In particular, how many ground-based personnel will be required, and what will be their roles?

The ratio of ground support personnel to airborne pilots needs to be considerably greater than the current 1:1 ratio of Captains to First Officers to make such an aircraft economically viable. This is a factor that has yet to be determined but will be determined by the degree of on-board automation/autonomy and the operational concept.

Koltz et al. [58] suggested a Harbour Pilot could handle four-six consecutive approaches, assuming no off-normal situations. Harris [66], modelling departures and arrivals based upon the movements of a UK low-cost operator at a busy regional airport, estimated that at least six Harbour Pilots per shift would be required to service that particular airline at that airport. Brouquet [67] proposed a of 5:1 ratio of ground operators to pilots, potentially rising to 7:1, but did not specify the system configuration. However, as discussed later, these simple support ratios disguise a wider operational issue. Nevertheless, it can be concluded that the simple remote piloting option is unlikely to result in significant savings as the ratio of remote pilots to airborne pilots is likely to be close to unity [34, 66].

3.2 Role of the pilot

The roles of the personnel in the system need to be established. The development of a single-pilot aircraft is a unique opportunity for a fundamental re-think of the role and function of the pilot. Organisationally rooted criteria for the allocation of functions [68] extend this issue beyond a simple technical consideration to the wider, socio-technical system. Over the years, the pilot's task has changed considerably from being a 'hands on throttle and stick' flyer to that of a flight deck manager, overseeing both the human and automation resources on board the aircraft. Direct control is often limited to taxiing and take-off/initial climb. In many instances even the approach and landing phase is automated.

It is likely that this trend toward the pilot becoming an automation/mission manager will be further exacerbated in the advent of SiPO. Harris [9] suggested that the role of the pilot will be that of a flight manager on both a strategic and tactical level; a communicator with air traffic management, airline and other authorities; and a surveillance operative. In the case of more autonomous systems, the pilot will set high-level goals and the aircraft systems will determine the best way to achieve them [47, 69, 70]. The key role of the pilot will be to evaluate the progress of the flight and the automated functions within the operational context and be a ‘sense checker’. Automated/autonomous systems will provide error oversight and system monitoring. In the case of equipment malfunctions they will re-configure the aircraft as required and evaluate the implications for the flight; however, the pilot will still be required when a flexible decision maker is needed in response to unusual situations. The more obvious instances of this can be observed in the manner in which the crew managed potentially catastrophic, highly unseen in-flight emergencies, such as the multiple failures in Qantas flight QF32 or US Airways flight 1549 [71, 72]. However, less obvious instances include flight re-planning where facilities become unavailable at short notice while at a destination airport or completely unforeseen in-flight occurrences, such as the sudden closure of all US airspace on 11 September 2001. The goal of the pilot-centric design of a single-pilot airliner is to keep the crewmember at the hub of the decision-making process with them being the ultimate authority [70, 73, 74]. Sprengart et al. [69] go as far as to suggest that this change in role should be reflected in a change in the title of the human operator on board the aircraft, from ‘pilot’ to ‘mission manager’. However, the skill set required to manage a single-crew aircraft will not be the same as that currently required to manage a modern airliner, which has implications for the selection and training of pilots.

4.0 Social acceptance: will people fly on a single-pilot airliner?

Passengers must accept the SiPO concept; otherwise, there is no reason for the development of such an aircraft. John Hansman, noted that “the issue has never been ‘Could you automate an airplane and fly it autonomously?’ The issue is ‘Could you put paying customers in the back of that airplane?’” [75]. Moehle and Clauss [22] argued that a major challenge lies in convincing both the regulators and the flying public that commercial single-pilot operations will demonstrate an equivalent level of safety as two-pilot operations.

There is little direct information available concerning the passenger acceptability of a single-pilot airliner, however there is related work on attitudes towards flying on UASs. Over the span of two decades there was a marked change in the attitudes of the travelling public concerning their willingness to fly in such aircraft. In 2003 it was found that only 10.5% of respondents surveyed would be prepared to be a passenger, although more than 50% expressed the opinion that the technology was acceptable for cargo, humanitarian and other commercial uses [76]. Twelve years later, 34.8% of potential passengers surveyed may be willing to fly on an autonomous airliner [77]. Nevertheless, it was again noted that passengers expected to see precursor systems operating safely beforehand. These figures are somewhat higher than those reported in an Ipsos poll commissioned by ALPA which suggested 18–27% of passengers would be willing to fly on a pilotless aircraft, depending upon the fare reduction made possible [11]. Two years later, it was reported that 69% of people surveyed indicated that they might be willing to fly in a pilotless airliner [78]. This research also attempted to identify the types of passengers willing (or unwilling) to fly on such an aircraft [78, 79]. Younger respondents and those with an interest in new technology, particularly those more familiar with autonomous systems, indicated that they would be most likely to fly in a passenger carrying UAS. Older passengers were more wary of the technology. However, these figures apply only to pilotless airliners. In another survey of airline passengers, 50% of respondents indicated that they would be willing to fly on a single-pilot airliner [80]. The main determinates of their intention to fly on a single-pilot aircraft were the health of the pilot; their trust in the technology, the ticket price and the reputation or the airline operating the aircraft.

Nevertheless, any decrease in perceived (rather than actual) safety by the public may serve to make a single-pilot airliner unviable. In addition to the airlines, other critical stakeholders also need to accept the concept, such as politicians, pilot unions and insurance companies [23]. Pilot unions have several concerns, mostly associated with the safety of the concept [11–13].

5.0 Safety assurance and regulatory challenges

With the exception of a few rules pertaining to competition and finance, the vast majority of regulatory requirements in aviation are specifically concerned with safety. These are also a primary concern of pilots' professional bodies [11–13]. The design and operation of SiPO aircraft are going to create new challenges requiring new, system-wide solutions.

The hazards related to SiPO need to be identified and then avoided or mitigated [81, 82]. Since 1977, the FAA has approved single-pilot light jets (below 12,500 lbs gross weight) to operate under 14 CFR Part 135. These are high-performance aircraft with sophisticated flight deck technology. Although these aircraft are by no means a match, Comerford et al. and Schmid and Stanton [23, 83] proposed that they have comparable avionics and complexity of operations to the proposed SiPO airliners. The experience gained and lessons learned from SJ's SiPO cannot be ignored. The National Business Aviation Association – NBAA [84] stated that SiPO in SJ was challenging. The NBAA risk analysis identified issues in single-pilot resource management (SRM), including essential skills such as task and workload management, maintaining situational awareness, automation management and risk management.

5.1 Safety

The single-pilot aircraft is just the airborne component in a wider system. Focus has naturally been on the aircraft and aircrew but under SiPO, safety issues extend well beyond this component to all aspects of the ground-based aspect of the operation.

Human-factors considerations such as workload, situation awareness and error are products of complex, inter-related systemic factors such as the number and difficulty of the tasks to be performed in the time available; training and experience; the usability of the flight deck equipment; interactions with the flight task and other stressors [85]. In SiPO, workload and situation awareness will also need to be considered as part of a distributed, socio-technical system [86]. Contemporary models of Distributed Situation Awareness [DSA] have suggested that it resides in both human and non-human elements right across a system, not just in the pilot [86–88].

The potential for increased workload (and specifically instances of workload peaks) has been identified as a safety concern for SiPO [11–13] and was recognised as a hazard in the operation of SJs [89] as was the removal of the second pilot (Pilot Monitoring) in their roles as an error checker and as a counter to pilot incapacitation. Using the harbour pilot configuration [47, 57, 58] a number of simulated flight trials showed that flight deck workload was within acceptable bounds and situation awareness was high. Harbour pilot workload was low [58]. Performance was maintained in a variety of different approach and weather scenarios. However, the resilience of a single-pilot airliner system was found to be inferior to the current two-pilot solution if there was not ground-based support in high workload, non-normal and emergency situations [55, 56, 64, 65].

There is a workload 'cost' associated with the management of flight deck crew; the Captain's role in promoting communication, coordination and cooperation has a workload overhead associated with it [53]. Doubling the number of pilots does not half the workload (and vice versa) but is does provide a workload margin. Modern flight decks are also already certificated to be flown by a single pilot in an emergency (FAR/CS 25.1523). SiPO simulated approach and landing trials in an Airbus A320 did not impose significantly higher workload on the pilots during normal operations but did impose greater workload in turbulent conditions and during abnormal operations. Error rates also increased in these situations [90]. However, workload management can be trained [89, 91].

However, the second pilot can also introduce errors on the flight deck and their overall effectiveness as an 'error checker' has also been questioned [92]. Moehle and Clauss [22] describe several instances where interactions between multiple crew members contributed to the subsequent accident. Poor CRM has been ascribed as a contributory factor in 23% of fatal jet aircraft accidents [93]. Omission or inappropriate actions were implicated in 39% of accidents and incorrect application or a deliberate non-adherence to procedures was implicated in a further 13%. Becoming 'low and slow' was a factor in 12% of accidents, and poor positional awareness was identified as a causal factor in a further 27%

of cases. These all imply a failure to cross monitor the flying pilot. Nevertheless, these accident data also fail to show the number of instances where the second pilot trapped an error: this is unknown and unknowable, and may occur several times on each flight. Put simply, this is good CRM. Nevertheless, observational data from routine commercial flights reported 47.2% of Captains' errors involved intentional non-compliance with Standard Operating Procedures (SOPs) and regulations; a further 38.5% were unintentional non-compliance [80]. It was also reported that more than half of all errors went undetected by one or both pilots. A similar study in the US [94] observed an average of 3.2 checklist errors per flight: 5.2 errors in the application of primary procedures, and 6.5 errors in monitoring. Error rates were more related to the number of procedures required rather than flight duration. It was noted that only 18% of these deviations were subsequently trapped and corrected. However, it was also observed that 89% of these errors had no discernible negative outcome and that the overall rate was probably only in the region of one percent. Error checking and pilot monitoring will be essential automated functions to incorporate into SiPO flight decks. To ensure safe and efficient coordination of ground and air resources, new forms of CRM will be required (Single Pilot Resource Management [84, 91]) to address issues such as risk management, automation management, task and workload management, and maintaining situational awareness.

A common concern for SiPO is associated with the incapacitation, impairment or ultimately death of the pilot. Fortunately, such instances are extremely rare. Between 1993 and 1998 there were only 39 instances of in-flight incapacitation and 11 instances of impairment in US airline pilots [95]. The overall rate of in-flight events encompassing both categories was 0.058 per 100,000 flight hours, and the probability that subsequently such an event would result in an accident was estimated to be 0.04. Flight safety was only seriously impacted in seven cases, resulting in two non-fatal accidents. The Australian Transport Safety Bureau's (ATSB's) accident and incident database contained 98 occurrences of pilot incapacitation between January 1975 and April 2006 [96]. These events resulted in 82 incidents and 16 accidents. All ten fatal accidents involved single-pilot operations but were concerned mostly with private or business operations. It was noted that medical standards for professional pilots were more stringent than those for commercial pilots. In the only fatal accident that involved a charter operation, incapacitation occurred as a result of hypoxia, not any pre-existing medical condition. A later study of UK commercial pilots suggested a much higher incapacitation rate than that reported in the US with the estimate of the annual in-flight rate to be 0.25% [97]. However, these data were not weighted by flight hour and the rate was expressed as the proportion of all UK pilots, irrespective of their flight hours.

All single-pilot aircraft will require ground support, even the more autonomous versions. There are potential safety benefits which accrue from the ability to assume control of the aircraft from a ground station. Revell et al. [65] describe the system redundancy afforded by the ground operator in the case of hypoxia (cf. the Helios Airways accident, 2005 where the pilots became incapacitated as a result of hypoxia following a cabin pressurisation incident). SiPO pilots will need to be continually monitored to support workload offloading [48–51] but this also has the benefit of supporting intervention from the ground in the case of incapacitation. Similar potential benefits also accrue in the instances of in-flight fire. In the case of a scenario such as the Germanwings pilot homicide/suicide, it can be argued that the ability to override the aircraft from the ground (or for the on-board autonomy to intervene) provides an additional layer of safety, rather than degrading safety [56]. Ultra-secure, high-speed data links will be required though to enable these benefits and assure a high degree of cyber-security.

5.2 Regulation

The current regulatory position is that SiPO for large commercial aircraft are not permitted. The regulatory challenges are manifold, but without regulation in place allowing for single-pilot commercial operations, there is no viable future for the concept. Moehle and Clauss [22] argue that the real challenge lies in convincing regulators and the public that commercial operations can be performed as safely with a single pilot as with two.

The future certification of a single crew airliner will pose considerable challenges. International agreement will be required to develop new aircraft and operating certification requirements (the requirement for two pilots is principally an operating regulation, e.g. 14 CFR Part 121.385: Composition of Flight Crew). Furthermore, the formulation of a new certification approach will be necessary to demonstrate the safety of the aircraft and its operation. A great deal of the certification and regulatory challenges will necessarily be directed towards the Human Factors aspects. A full discussion of the related challenges is outwith the bounds of this paper, but SiPO will impinge on most aspects of the regulatory system, from design and certification, to operations and training, including approval of simulation facilities. All are inter-related. Current regulations (for example flight time limitations) may need to be modified if it is found that SiPO is more fatiguing than multi-crew operations, even though sectors are likely to be quite short. New areas of regulation and certification will also be required for the non-airborne components of the system.

Existing certification methods are limited in their capability to address the safety issues and evaluate the range of solutions that are likely to be implemented in SiPO. Current certification approaches regard the aircraft as a standalone component. However, the single-pilot aircraft is just one component in a wider operating system, which will also include ground-based components that will have a direct effect on the safety and efficiency of operations. A new regulatory approach to safety assurance will be required. In the same manner as the safety assurance of UASs, the airborne component cannot be considered alone [98, 99]. One proposed pathway to certification incrementally changes the focus of control from the pilot to the automated systems/autonomy in the aircraft in the event of a pilot becoming overloaded or incapacitated [100]. From a certification perspective this has the benefit of keeping all the systems to be assessed in the aircraft itself which is commensurate with the current aircraft certification ethos (c.f. Harris [101] who suggested that control should transfer to the ground). It also has benefits, providing less reliance on high-integrity, high-speed data links required by the distributed crewing design approach. However, it does not preclude ground-based systems from being incorporated into any safety assessment as an adjunct.

From a Human Factors perspective, a coherent link between aircraft design, training and operations is required to enhance both safety and efficiency. These issues are complex, highly inter-related and multifaceted. Further regulatory initiatives will be required which extend beyond the aircraft. Operating a single-pilot commercial aircraft will require a re-distribution of tasks between the air and ground, and the pilot and machine. These will not just simply be flying tasks, but also flight management activities, coordination and wider personnel management duties. Control and surveillance data will be swapped in real time between the air and ground components. As a result, a safety case approach will probably be required to supplement the certification of the aircraft component itself [98, 99, 101]. Such a ‘top-down’ approach focuses on critical issues that affect specific safety targets, addressing complex interactions between the human, non-human, air and ground-based components in the system. Hazards are addressed by a combination of design and operational requirements and are constrained by the need to comply with a code of requirements for individual aspects of the system (cf. those in the certification requirements in FAR/CS Part 25). They are not prescriptive in the manner by which safety is demonstrated. The objective is to demonstrate that systems meet a defined safety goal. This approach is used for the safety assessment of UASs [98, 99]. Furthermore, the basis for safety cases is being used by airlines as part of their Safety Management processes. In the case of SiPO their root causes and amelioration will extend beyond the flight deck to the ground support elements.

As an example, under SiPO, ground-based personnel, such as Dispatchers, will now perform a safety-critical role in the operation of the aircraft. In the US, the FAA certificates Ground Dispatchers, requiring formal training and testing. The FAA Aircraft Dispatcher Certificate already requires knowledge of subjects such as meteorology; interpreting weather charts and forecasts; interpretation and usage of NOTAMs; air navigation in IMC; ATC procedures; aircraft performance, weight and balance calculations; aerodynamics; Human Factors, aeronautical decision-making and CRM. There is no such equivalent qualification in Europe. In the case of SiPO the function of the Dispatcher will need to be extended. In Europe it is likely that formal qualifications (and recurrent testing) will need to be developed. As another instance, consider the single-pilot airliner flown using the Harbour Pilot concept of operation. To become a Maritime Harbour pilot serving a major port, seafarers are usually required to hold an International Maritime Organisation Master's qualification and have served as Captain or Chief Officer on a merchant ship. In the UK the pilot has the legal conduct of the ship in their designated waters and is responsible for directing and executing a passage plan, and directing the speed and course of the vessel. Similar knowledge and qualifications will be required of an airline Harbour Pilot; however, it is not clear if such a role is aircraft type-specific.

A regulatory challenge will be to provide a system-wide safety assurance approach for SiPO while maintaining the safety advances made using the current certification systems. Harris [101] has described one potential method to such a system-wide certification that integrates the current 'system-by-system' certification approach with a safety case-based methodology.

5.3 Regulatory capture?

Regulatory capture is the process by which influential institutions manipulate regulatory agencies to their benefit. The FAA was accused of failing to provide independent oversight and regulation in the cases of the Boeing 737 MAX, specifically the Maneuvring Characteristics Augmentation System (MCAS) which was designed to prevent an excessive angle-of-attack developing [102]. However, SiPO will be dependent upon wider, international regulatory changes and agreement.

Regulatory change needs to keep pace with that of technology development, but the question arises if single-pilot aircraft are simply a financial and operational sinecure to address the issues described in the opening section at the expense of safety. However, the development of SiPO technologies and operational concepts can also drive the development of new flight deck equipment for multi-crew aircraft and encourage safety to be examined in a more integrated fashion, adopting a holistic air/ground perspective [7, 101], which is beneficial for current operations. Reductions in flight crew complement in the past have been accompanied with step changes in technology (e.g. two-crew aircraft and the introduction of first generation, 'glass cockpit' aircraft using flight management systems [103]. The net result has usually been a decrease in the accident rate [104].

Regulators are adopting a pro-active approach to the safety analysis of potential SiPO [4], however this is driven by manufacturers developing the technology and airline interest. Searching for economy by reduction in personnel numbers is nothing new and is fundamental to many human-factors related activities [105]. Where this legitimate operational strategy becomes the more questionable practice of regulatory capture is moot, but the latter certainly need to be recognised if it is to be avoided.

6.0 Organisational challenges for single-pilot operations

The economic, technological, regulatory aspects and the societal acceptance of the SiPO concept have already been discussed. However, a fifth aspect also needs to be addressed: the organisational aspects of the operation of such an aircraft in airline service. In SiPO, enhanced ground support will also be required which will involve the redesign of the roles and responsibilities of both the pilots and ground staff [106]. This will cover issues related to function allocation, human–autonomy teaming, and procedures for normal and off-nominal situations. Harris [8], taking a wider Human-Systems Integration approach, identified several areas not directly associated with the design of the aircraft per se but which must be addressed if a SiPO airliner is to be workable. In this perspective, the single-pilot airliner is regarded as just one (but central) component in an air transportation system for the movement of people and goods. The aircraft is at the centre of a wider-socio-technical system.

Removing one of the pilots has ramifications across a number of operational areas not directly related to flying the aircraft. Operating this new category of aircraft (irrespective of the technological approach adopted) will require re-distribution of tasks between the air and ground personnel, and the pilot and machine. For example, pre-flight briefings, verification of the flight plan, review of meteorology, NOTAMS (Notices to Airmen) calculate the final fuel load, etc. can take up to an hour for two crew sharing these tasks. Once at the aircraft, one pilot must conduct an external check of the aircraft's condition. These issues can partly be addressed by a mix of task reallocation (e.g. the walk around could be delegated to an engineer; verifying the load sheet could be re-allocated to a dispatcher) and the use of technology; however, this has legal implications as the captain must sign to accept the aircraft. Furthermore, while these activities may be re-allocated the impact of doing so needs to be evaluated. For example, Situation Awareness builds over time and the progress of the flight: it does not happen instantaneously. It determines what they attend to, which dictates how subsequent information is actively sought out and interpreted [85, 107]. This starts with the flight plan and NOTAMS.

A key operational determinant will be the number of ground staff required to support the fleet of single-pilot aircraft. Some estimates for the ratio of pilots: ground-based staff have been suggested earlier [58, 66, 67]; however, this an over-simplistic view. How many and what the roles of ground-based personnel will be will depend upon the configuration of the aircraft and its concept of operation. Of the two broad approaches described, the more technologically cautious distributed crewing philosophy will probably utilise more ground-based staff than the highly automated/autonomous systems-based approach.

The distributed crewing approach will potentially be easier to certificate (safety-assure) being based largely upon extant, well-established technologies. However, it will require the development of new organisational roles and structures which, at the same time, will result in a decrease in operational flexibility. In this respect it is worth considering the implications of the Remote Pilot concept versus the ‘Harbour Pilot’ concept [34, 47, 58, 63]. The remote pilot approach involves the ground pilot (or ground support team) providing support for the flight from take-off to landing. In this case a potentially simple ratio of pilots: ground support may be derived, however careful operational scheduling is required. Highest levels of assistance will be required in the taxi-out, take-off, approach and landing phases. A ground-pilot will probably need to provide dedicated support during these phases, so the number of ground-based personnel required will depend upon the number of simultaneous take-off and landings occurring across the airline fleet at peak times. Additional capacity will also be required for ad hoc enroute support and spare capacity to deal with non-normal situations and emergencies. In summary, to be commercially viable, the overall number of personnel employed in the airline for SiPO must be lower than the equivalent number for multi-crew operations, and/or be lower salaried posts.

Estimating the degree of support required for SiPO utilising the Harbour Pilot concept is more complex. Harris [64] describes some of these issues. For a large, low-cost airline based at a UK regional airport, modelling estimated that this would require six Harbour Pilots per shift (three shifts) to support 132 movements/day if Harbour Pilots were used flexibly to support both departures and arrivals. This was only for this airline, at this airport and assumed a homogeneous fleet of aircraft. Considerably more ground-based personnel would be required under the tripartite model [60]. Harbour Pilots would also be required at the destination airports, which would severely limit the number of destinations and decrease flexibility of the single-pilot aircraft using this approach. To make it an economically viable option (particularly for thinner routes) would require Harbour Pilots to be engaged by the airport, rather than the airline. This would also require them to be non-aircraft type specific (q.v. the role of the maritime Harbour Pilot) and non-airline specific. This does, however, create further operational issues.

The selection and training of pilots is critical to ensure operational safety. Regional airline First Officers are often less-experienced pilots building hours. It may be prudent to mandate a minimum number of hours before piloting a single-pilot aircraft [21]. NBAA [84, 91] has developed training curricula specifically for pilots of Very Light Jets flown by a single pilot. Schmid and Stanton [83] describe a few of the potential training requirements envisioned for SiPO, but these are predicted upon the assumption that any remote pilot’s functions would essentially be the same as those required by a conventional pilot on board [57, 60]. However, depending upon the operational configuration, this may not be the case.

Currently, the regime for pilots is based upon pilots training in the flight simulator as a team of two [108]. SiPO will still require pilots to be trained as part of a team during certain flight phases (e.g. departure and arrival, during high workload operations, and in non-normal and emergency situations); however, team members will now be physically separated, communicating via simulated datalink.

Ground support (also undergoing training) will probably use dissimilar ground system user interfaces to those in the aircraft itself. Furthermore, the ground-based support may not be a pilot, but some new role. In the case of the 'Apollo 13' distributed team architecture, the specialist ground operator may call on a wider network of support from the AOCC, presenting further training challenges. This will require new LOFT (Line-Oriented Flight Training) facilities and scenarios. Particular demands will be placed upon training ground operators handling several aircraft at once and liaising with other personnel in the AOCC. Training facilities, LOFT training scenarios and non/off-normal training where the ground-based support is provided by a Harbour Pilot will be particularly challenging, especially if the Harbour Pilots are provided by the airport/air traffic provider, rather than being airline staff. New CRM concepts and practices will need to be developed to support LOFT training [91, 109]. Establishing SiPO operations will require significant capital investment by airlines not just in the aircraft but in developing staff and new facilities to support its operation.

In the case of the single-pilot airliner, all pilots will be captains, but there is more to being a Captain than just being a pilot. The Captain is responsible for the flight, the crew, the passengers and the aircraft. When away from their main operating base they are responsible for liaising with the airline and coordinating many activities at the destination airport. They are a resource manager as well as a pilot. As the co-pilot role ceases to exist in a single-pilot concept, the question arises as to how single pilots would gain the necessary experience to operate safely as Captains without an airline also maintaining conventional two-pilot operations.

7.0 Conclusions

The momentum behind SiPO is increasing for financial, operational and increasingly, environmental reasons. The ATI suggest that cargo operations may commence in the early 2030s, followed by passenger flight five years later. Much of the technology is being developed or is already available. However there remain fundamental issues to be addressed concerning the safety of the concept and its societal acceptability. Ultimately, these issues may be resolved. From a review of the various proposed SiPO configurations, Vu, et al. concluded that "*Although no single concept has been shown to be superior, the studies reviewed here show no real "show stoppers" in moving toward SPO* {Single Pilot Operations]" [110]. However, there remain operational challenges that may determine if the concept is ultimately viable from an airline perspective.

From an operational perspective, prospective analyses need to be undertaken to identify hazards and develop methods to avoid or mitigate them to assure safety. Hazard analyses based upon the operation of Very Light Jets may produce a useful source of data in this respect [4, 84]. Results from such hazard analyses will further serve to drive SiPO design, operational and training concepts.

High levels of automation/autonomy will be required for SiPO. The problems associated with the management of automation on the flight deck have been identified are researched since the implementation of glass cockpit aircraft. However, the issues related to the management of autonomous systems on the flight deck are less well understood. These systems are non-deterministic, so cannot be managed and monitored in the same way. Research needs to be undertaken to determine design, management and training strategies for flight deck autonomous systems.

However, irrespective of the system configuration employed, the biggest change in SiPO will be the increased coordination required between air and ground components. This will be essential for safe and efficient operations. The nature and methods of air/ground communication and coordination will require extensive research and development.

The distributed crewing approach, based upon extant UAS and military technologies will be quicker and cheaper to develop, and contain fewer technological unknowns, enhancing the likelihood of its certification. This approach is also commensurate with operating concepts in major airlines, where aircraft are supported by staff in an operations centre. However, irrespective of the SiPO concept of operations, this approach will require a great deal more support from the ground, with personnel involved in a variety of new or extended roles. This will place demands on new training facilities, personnel licencing, safety assurance and other organisational structures while at the same time imposing limited flexibility in operations, especially if a Harbour Pilot concept is adopted. This may limit (or negate) many of the potential economic benefits of SiPO, especially those associated with opening up thinner routes into remote airfields (ACARE FlightPath 2050 goals [111]). Overall operations may become more complex and involve more staff (especially in non-flying roles).

The more complex approach to SiPO based around the extensive use of autonomous systems may take longer to develop and pose considerable certification challenges to demonstrate its safety. However, it is ultimately likely to require less support from ground-based personnel and present fewer organisational challenges for airlines, in terms of new ground-based roles, training demands and operating structures. As a result, it will also be operationally more flexible, not requiring new roles (e.g. Harbour Pilots) that may limit route options, especially to more remote, less well-equipped airfields. Furthermore, there will be less of a requirement for high integrity air/ground data links (more secure – reduced cyber threat).

The safety issues associated with the introduction of SiPO can potentially be overcome. The technology on the ground and in the flight deck is well understood or is currently in development, but is largely derived from known applications. New aircraft designed specifically for SiPO will incorporate specifically developed technology to support the pilot. The operational and organisational practicalities associated with the introduction of SiPO may be a greater obstacle, though. Initial set up costs may be significant, particularly in the case of the distributed crewing approach. Designing and building the aircraft may be the easy part: operating will be the challenge.

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