Progressing towards Airliners’ Reduced-Crew Operations: A Systematic Literature Review

**Objective**: The present article undertakes a systematic review of the current state of science for Single-Pilot Operations (SPO) and Reduced-Crew Operations (RCO) in commercial aviation.

**Background**: SPO/RCO have been investigated with different methods from various disciplines and different organizations of making research progress. The results of federal agencies’, universities’, and EU-projects’ research activities have not been brought together for synthesis yet.

**Method**: We systematically searched for SPO and RCO as independent and fixed search terms retrieving altogether 75 publications on the topic. Exclusion criteria were general and military aviation.

**Results**: Establishing an appropriate function allocation to cope with high workload and off-nominal situations could be achieved by applying a variety of methods and the consideration of advanced automation systems. Their application is required to investigate pilot incapacitation and communication issues further. Data-link and certification issues were acknowledged in principle and have not been solved yet.

**Conclusion**: In sum, experimental studies and modelling techniques of system ergonomics have addressed operational issues very well. Pilot health monitoring systems are less well elaborated than system protection. Future research needs to integrate different research findings and automation technologies. This is necessary to make RCO to a viable and attractive option for commercial development in aviation.

Keywords: single-pilot operations; reduced-crew operations; commercial aviation; transport aircraft

*Word count: 6,294*

# Introduction

A continuous de-crewing on the flight deck has characterized the history of commercial aviation. In the 1950s, early long-range aircraft equipped with much more analogue instruments and controls required a flight crew of five specialists for safe operations: the pilot, copilot, flight engineer, navigator, and radio operator (Bohn, 2010). Each of them integrated detailed information from the displays and controls to perform the necessary mission tasks (Boy, 2016). After they had been automated and integrated into the two pilots’ duties, the two-crew flight deck became modern standard.

During the last decades, the level of sophistication of instruments and automation systems that support the pilots in different tasks has increased (Jacobsen, Graeber, & Wiedemann, 2010). Around 1990, the second generation of glass cockpits was set up with the Airbus A320 and Boeing 747-400. Advanced automation systems, data-link displays and controls, multifunction displays, and fly-by-wire flight controls complemented the flight crew’s tasks by increasing safety and efficiency. At the same time, costs were reduced. The Airbus A350 and Boeing 787 present the latest version of glass cockpits with fully integrated electronic flight bags as on-board information systems (Airbus, 2011a). These flight decks have become integral part of the safest transportation system in the world.

Following the evolutionary approach toward Single Pilot Operations (SPO), the crew size of a modern airliner could be reduced further by removing the copilot while maintaining the current level of system safety (Boy, 2015). Various factors contribute to current flight safety and a low accident rate compared to decades ago (Abbott, McKenney, & Railsback, 2013; Boeing Commercial Airplanes, 2018; Ranter, 2019). Among them are standard operating procedures, flight deck design (including the Flight Management Systems: FMS), a regulatory communication framework, training and certification, as well as the operational redundancy provided by the second pilot on-board. In fact, the redundancy adds an essential safety value to the operation of airliners although Pilot Flying (PF) and Pilot Monitoring (PM) duties, responsibilities and functions may differ slightly across operators. For example, the two pilots enable cross verification of data entries into the FMS (which in itself is insufficient to prevent hazards resulting from mis-entries: International Air Transport Association [IATA], 2011). Especially during high workload situations, entries into the FMS require a specific function allocation among the two pilots depending on situation, professionalism, and operating procedures (IATA, 2015). Accordingly, pilot interactions within automated commercial Multi-Crew Operations (MCO) contribute to safety. Nonetheless, research has already begun on SPO for commercial airliners (Harris, 2007).

The demand for air transport is continuously growing (Airbus, 2018; Boeing, 2018). Against this background, SPO could provide an economic benefit in the long term by saving operating costs. This benefit concurrently represents one metric of function allocation during design (Pritchett, Kim, & Feigh, 2014a). Firstly, an extrapolation of annual flight crew costs to a 20 year service life of an aircraft shows that crew costs can represent a large share of a new aircraft’s market value from which SPO could benefit (Norman, 2007). Secondly, a cost estimation model for possible SPO on current one-year-basis showed a small savings potential for an optimistic scenario including a remote-pilot (Malik & Gollnick, 2016). Thirdly, the aggregation of a life-cycle costs model, a reliability analysis and an evaluation of a flight procedures model in terms of time on task supported the single-pilot crewing option (Graham, Hopkins, Loeber, & Trivedi, 2014). SPO are most likely to reduce operating costs, maintain or improve flight safety, as well as maintaining airline serviceability. All analyses agree that there are cost benefits for SPO, at least in the longer term. Although they used different methods, none incorporated the costs required to develop and provide a human-centred aircraft, operations and procedures, and the corresponding infrastructure. Since a retrofit of current aircraft models to SPO is not economically viable SPO can only be developed for future models (Driscoll, Roy, & Ponchak, 2017). New developments in avionics equipment could accommodate SPO requirements or provide the option to add them later. Beyond that, the predicted pilot shortage has only been mentioned on the edge as a motivator for proceeding to commercial SPO to reduce crew costs (Graham et al., 2014; Harris, 2017).

These practical implications are opposed to research implications which arise from finding a solution to preserve and refine operational safety of an airliner with a reduced flight crew. Some of the PM’s functions in SPO have to be distributed to either on-board automation of the single-pilot aircraft or ground-based systems operated by a remote operator (Harris, 2007). A single-piloted aircraft requires support in high workload situations to overcome the lost redundancy of the second pilot. The second pilot’s error checking function is completely removed, which is why the role of the pilot in the air requires a re-conceptualisation.

About two decades ago, research has started working at solutions on how to overcome the loss of redundancy of a second pilot (Harris, 2007). Most activities were mainly conducted in academic units and commercial SPO have not entered industrial development yet. Currently, the single research units are fragmented and influences of other neighbouring areas have not been considered into the on-going projects. Thus, there is a need for a comprehensive and systematic view on SPO including theoretical discussions and practical applications and evaluations because no one has integrated the research results from the fragmented research units.

The present paper aims to bring together all research conducted regarding commercial SPO until now to assess the current state of science. It further elaborates the main issues of SPO’ areas of research and clusters how far developed they are. The systematic literature review used the five research issues unique to SPO (Johnson et al., 2012): operational issues, automation issues, pilot incapacitation, social/communication issues, and certification issues. For each issue, studies are synthesized by comparing their results to identify current limitations and future research needs. This comprehensive picture on the anticipated future SPO should stimulate debate and foster new research insights.

A systematic literature search was conducted (see Table 1). We included all peer-reviewed studies regarding commercial aviation. Exclusion criteria were general (except business) aviation and military aviation. Military aviation is different to commercial operations because the operational environment of fast jets is unique and different in its complexity, such as its agility and tactical missions (Newman, 2014). General aviation differs in terms of the operational environment as well due to less strict scheduling, different missions, conditions and characteristics of aircraft. In addition, private pilots are less often exposed to many types of flight operation, receive less formal training and oversight compared to their commercial colleagues (Schutte et al., 2007). Hence, we only included aircraft related to business aviation which are similar in complexity and type of operation, such as Embraer’s (2015) light jet Phenom 300. Their flight deck systems are comparably equipped with FMSs and glass cockpits certified to transport up to 9 passengers under SPO.

Table 1. Literature research with corresponding syntax and field.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Field: Syntax** | **Search** | **Result Count** | **Action** | **Identified articles** |
| Topic: single-pilot operations OR "single-pilot operations" OR reduced crew operations OR "reduced-crew operations" | Web of Science | 482 | All titles reviewed | 32 |
| Google Scholar | 3,090 | Titles of top 1000 most relevant reviewed | 42 |
| Article Title, abstract, keywords: ~ | Scopus | 639 | All titles reviewed | 48 |
| All fields: single pilot operations AND reduced crew operation AND aviation | Scopus | 120 | All titles reviewed | 25 |
| “Single-pilot operations” OR “Reduced Crew Operations” AND “business aviation” | Google Scholar | 66 | All titles reviewed | 8 (4) |

*Notes*. The ~ indicates that the same search term syntax as above was used for the search engines. Not-peer-reviewed literature was only included when directly relating to commercial SPO. Furthermore, conference papers were classified as peer-reviewed because most articles fell under this categorization. Additionally, the cited by references were examined of the journal articles and added. The results were retrieved at 19 July, 2019.

Hereafter, we use the more comprehensive term of Reduced-Crew Operations (RCO) to refer to commercial SPO. Whereas the term SPO refers to having only one pilot on the flight deck of an aircraft the more inclusive term RCO includes relief pilots additional to a single-pilot on-board on long-haul and ultra-long-haul flights (Schmid & Stanton, 2019a).

# Operational Issues: Designing Ground-based Support

One of the main operational challenges in RCO is to overcome the lost redundancy of the second pilot in MCO (Comerford et al., 2013; Harris, 2007; Johnson et al., 2012). This is why a new Concept of Operations (ConOps) is required. Flight safety must be guaranteed while the functions have to be allocated differently for the single-pilot aircraft automation, and where applicable, for remote operators. Function allocation is defined as deliberate design decisions about assigning work functions to the human and automated agents of a sociotechnical system (Feigh & Pritchett, 2014; Pritchett, Kim, & Feigh, 2014b). These allocations should keep workload in an acceptable safe range for each part under different temporal dynamics (Young, Brookhuis, Wickens, & Hancock, 2015). Each agent must be capable of performing assigned tasks and conducting teamwork successfully. This concerns different aspects in operator, team and system performance that characterize system operations (Salmon, 2016). Most prominent examples are mental workload (Young et al., 2015), Situation Awareness (SA; Stanton, Salmon, Walker, Salas, & Hancock, 2017), and trust in the system and its automation (Schaefer, Chen, Szalma, & Hancock, 2016). Until now, different ConOps have shaped the research in RCO of which operator, team, and system performance have been investigated to varying extent from the individual and system ergonomic view. In this paper, we have assessed the reduced-crew ConOps against the issue of function allocation in order to gain further insights into their effects on RCO. Table 2 shows the published literature sorted by topics sorted by methodological approaches.

During early research stages, a ConOps without human ground-based support abandoned for three main reasons. Firstly, SPO represent a modern but less-widespread operational practice of a few business jet models (Burian & Dismukes, 2007). These aircraft models synonymously referred to as Very Light Jets (VLJ) can be optionally operated under 14 C.F.R. Part 135 by having only one pilot on-board (Federal Aviation Administration, 2017). They are limited to a maximum of 9 passenger seats excluding CAT II and CAT III approaches. Ground support is not foreseen. Integrated avionics solutions like the Prodigy® Touch Flight Deck at Embraer’s (2015) Phenom 300 characterize the flight deck design. The peer-reviewed, publicly available, research is limited and has only considered Single-Pilot Resource Management (SRM) to manage workload properly (Burian, 2007; Burian & Dismukes, 2007). Other efforts pointed out a lack of international VLJ training practices (Barnes, 2008; DeMik, Allen, & Welsh, 2008). The distribution of workload on the single-piloted flight deck has remained an issue when in real-world accidents. Exemplary accidents of aircraft operated under SPO of Part 135 happened as consequence of very high workload on the single-pilot during descent (National Transportation Safety Board, 2016) and approach (Aircraft Accident Investigation Branch, 2016). Hence, the current operational practice of single-piloted business aircraft including its automation cannot be transferred to be applied to commercial air transport yet. Furthermore, practical experiences in SPO for business jets are too limited for this purpose. Consequently, contemporary approaches to a reduced-crew ConOps have considered other possibilities for reducing the flight crew.

Secondly, the overall system’s resilience of future RCO without any ground-based support during high workload during off-nominal and emergency situations was found to be inferior to alternatives including such support (Harris, 2018; Revell, Allison, Sears, & Stanton, 2019; Schmid & Korn, 2018; Schmid & Stanton, 2019b; Stanton, Harris, & Starr, 2016). Different accident modelling methods from systems thinking in ergonomics were used predictively to identify systemic weaknesses (Grant, Salmon, Stevens, Goode, & Read, 2018). Although all studies included extensive materials on system architecture and operations as well as being validated by commercial pilots as Subject Matter Experts (SMEs), the methods lacked any formal empirical evaluation (Salmon, Walker, Read, Goode, & Stanton, 2016). Consequently, these models from system ergonomics urgently require validation in a simulated environment. Thus, the analyses represent a rather formative approach to initial system design supplemented by descriptive approaches to model selected aspects in detail (Harris, Stanton, & Starr, 2015; Huddlestone, Sears, & Harris, 2017; Stanton et al., 2019). Nonetheless, the models do show that the current cockpit configuration in combination with contemporary procedures cannot simply be transferred to RCO (Stanton et al., 2019). Nevertheless, the modelling work has confirmed the need for a ground-based support component in RCO.

Finally, empirical human-in-the-loop simulations quantifying workload during different emergencies in RCO should be compared to conventional MCO in order to demonstrate the benefits as well as confirm the need for remote support of a single-piloted aircraft (Bailey, Kramer, Kennedy, Stephens, & Etherington, 2017; Faulhaber, 2019). All of the modelling approaches to RCO (Revell et al., 2019; Schmid, Korn, & Stanton, 2019; Schmid & Stanton, 2019b; Stanton et al., 2016) made allocating functions design decisions in a deliberate, auditable and coherent way. Empirical simulation studies examining RCO should help to evaluate the design decisions and assist in the derivation of future design recommendations. The metrics of workload, coherency in design, and system costs are implicated in function allocation decisions (Feigh & Pritchett, 2014; Pritchett et al., 2014b). Different human-in-the-loop simulations have already focused on single aspects in reducing the crew, as illustrated in Table 2.

Table 2. Design approaches to RCO clustered by research units and study phases.

| **Reference** | **Design** | **Method** | **Manipulated variables** | **Measured variable** | **Outcome (only meaningful results)** |
| --- | --- | --- | --- | --- | --- |
| Harris (2007) | A human-centred design agenda for RCO | Viewpoint | Review of the literature | Re-conceptualisation of flight deck and role of the single-pilot is required for SPO | |
| Huddlestone, Harris, Richards, Scott, and Sears (2014) | New notation for representing hierarchical task decompositions of MCO | HTA | MCO (all flight phases) | Detailed analysis of current, two-pilot operations | Identification of functions, their allocation, and interactions |
| Harris et al. (2015); Revell, Stanton, and Kelleher (2016) | Use of OESDs to represent RCO | OESDs | Crew complement (MCO, RCO) | Function allocation of RCO | Description of RCO’ interaction in normal, non-normal and emergency situations |
| Stanton, Harris, and Starr (2014); Stanton et al. (2016) | Four different design concepts | CWA and SNA | Ground operator, system mirror | Function allocation, SNA statistics | Function allocation, macro network resilience |
| Revell et al. (2019); Revell, Allison, Stanton, and Sears (2016) | RCO with a ground support by a remote copilot | STAMP and STPA | Rapid decompression scenario | Safety constraints, unsafe control actions | A model for rapid decompression event in RCO |
| Huddlestone et al. (2017) | All flight phases in MCO and in SPO with one ground pilot | OESDs and WDA | Crew complement (MCO, RCO) | Normal actions, significant environmental conditions, interactions | Description of RCO’ interactions in normal and off-nominal (e.g. weather conditions) situations |
| Schmid (2017); Schmid and Korn (2017) | The introduction and discussion of the operational issues of a concept of RCO | Concept | – | A workload-centred concept for ground support by a remote-copilot and specialized ground operators | |
| Harris (2018) | Network re-analysis of Boeing 737 accident at Kegworth | AcciMap and propositional networks | Different SPO configurations | Propositional networks of accident scenario | Single-pilot with one remote-copilot can alleviate workload with effective communication. The more agents the more important is the coordination of the same. |
| Schmid and Stanton (2018, 2019b); Schmid, Vollrath, and Stanton (2018) | RCO with ground support by a remote copilot | STAMP and STPA | Scenarios (pilot incapacitation/ homicide-suicide; laser attack); crew (MCO/RCO) | Safety constraints, unsafe control actions | A model for reacting to pilot incapacitation, homicide-suicide, and a laser attack in RCO during approach |
| Schmid, Korn, and Stanton (2019) | Function allocation | CWA and SNA | Crew complement (MCO, RCO) | Function allocation, SNA statistics | Functions are allocated to single-pilot and a remote-copilot supporting mandatorily departure and approach |
| Schmid and Korn (2018) | Possible communications during normal operations modelled as social network | SNA (and CWA) | MCO, RCO, RCO data-link break-up | Functional loadings of agents, network statistics | Data-link break-up decreases the resilience of RCO in social network terms |
| Schmid, Korn, Wies, and Stanton (2019) | The possible detection, reaction and classification of data-link issues in RCO | STPA | Scenario: partial data-link outage, simple, and complete loss | Possible control actions for the three different data-link issues | Candidate technologies for handling different types of data-link issues anticipated in RCO |
| Stanton, Plant, et al. (2017); Stanton et al. (2019) | Observation of cargo short-haul operations from gate to gate under normal conditions | EAST | – | Interactions and communications | Some initial suggestions for distributed crewing’s task allocation including one remote-copilot are made |
| Schmid and Stanton (2019c) | Systematic review of suggestions of training of RCO operators | STAMP | Control loops related to training | A job rotation of single-pilot and remote-copilot will be beneficial to counter skill degradation. A special training fleet could include the current apprenticeship-style training into SPO. | |
| Schmid and Stanton (2019a) | Discussing fatigue as issue in RCO | Viewpoint | – | Depending on a proper fatigue management RCO are suggested to be extended to different flight lengths with respect to the distinct ConOps that might be applied in future. | |
| Deutsch and Pew (2005) | Initial recommendations for a research agenda to design operating procedures for RCO | Review | – | Research agenda, relevant technologies, software framework for the implementation of the automation. Role of copilot has to be reconsidered in communication and monitoring functions | |
| Schutte et al. (2007) | Design approach to an integrated flight system concept (Naturalistic Flight Deck; NFD) | Review of technologies | Only for small aircraft (VLJ) | Merely a ConOps for VLJs: performing the flight, flight planning, dealing with unexpected events. No remote support but an autonomous emergency landing in case of incapacitation | |
| Comerford et al. (2013); Johnson et al. (2012) | Three-day meeting including invited speakers, workshops, and workgroups | Technical interchange meeting | Coordinated and hosted by NASA | Stakeholders from the aviation community | Identification of issues and recommendations for RCO |
| Wilson, Harron, Lyall, Hoffa, and Jones (2013) | Exploration of the possibility to change Part 121 and Part 125 operations for certification under SPO | Interviews, review of airworthiness and operations regulations | Regulations: 14 C.F.R. Parts 25, 121 and 125 | Any SPO ConOps is not consistent with some of the current 14 C.F.R. Parts 25, 121 and 125. They would have to be changed or an equivalent level of safety would have to be demonstrated. Hereby, each new vulnerability or opportunities have to be considered for certification. | |
| Bilimoria, Johnson, and Schutte (2014) | NASA ConOps: a team of ground operators | Concept description at macro level | – | (1) Conventional dispatch of multiple aircraft, (2) distributed piloting by a super dispatcher of multiple aircraft, (3) dedicated piloting by a remote-copilot of a single off-nominal aircraft | |
| Lachter, Battiste, et al. (2014) | Impact of loss of non-verbal communication | Experimental simulation | Separation of pilots crew | Real and post-trial workload, decision making, confusion, | Higher confusion and less acceptance of separate condition |
| Koltz et al. (2015) | Harbour pilot concept as a type of dedicated support | Experimental simulation | Task load of operations, role (PF/PM) | Workload (NASA-TLX), SA (SART), feasibility rating, | About 4–6 arrivals can be support successively. Low-rated feasibility. |
| Brandt, Lachter, Battiste, and Johnson (2015) | Pilot situation awareness in SPO and its implications for further research | Experimental simulation | Hybrid operator with/without preview, Specialist no preview | Real-time SA probes, workload ratings (every 2-4 min) | Workload was lower for hybrid *multi-aircraft support*. SA is not to an issue when system and environmental data are present. |
| Lachter, Brandt, et al. (2014); Ligda et al. (2015) | Collaboration tools of a designated GS | Experimental simulation | Crew configuration (MCO, RCO, RCO + tools) | Operational performance, communication | Subjective ratings: RCO with collaborations better, preference for MCO; no workload differences |
| Gore and Wolter (2014); Wolter and Gore (2015) | Task analysis of scenarios of NASA ConOps simulations | Cognitive task analysisa | MCO, specialist ground operator, hybrid ground operator | Cognitive tasks of six different scenarios | A comprehensive description of all flight phases for three crew configurations |
| Schutte (2015) | Critical high level function allocation of the pilot’s task in current MCO | Viewpoint | Some general discussions | A critical review on the pilot’s role and function allocation in general. Less comprehensive | |
| Sadler et al. (2016) | Autonomous Constrained Flight Planner (ACFP): Trust in re-routing function and its recommendations | Low fidelity simulation | Transparency, level of risk | Trust (7-items scale), behavioural/performance measures | Trust increased with higher transparency; increasing transparency fostered pilot’s decision |
| Lyons et al. (2017) | High fidelity simulation | Transparency (no, probability, explanation ) | Trust (7-items scale) | Higher levels of transparency engendered higher trust into tool |
| Lachter, Brandt, Battiste, Matessa, and Johnson (2017) | Summary and review of all studies of the NASA ConOps mentioned above | | | | |
| Jay et al. (2016) | HAT pattern for nominal and routine off-nominal operations | HAT | RCO design (NASA ConOps) | Several HAT design pattern elements | Can be used to develop system designs, two varieties of cooperative links (collaborative and coordinative) |
| Brandt, Lachter, Russell, and Shively (2017); Shively (2017) | HAT pattern for a flight following task in RCO at dispatch GS (with ACFP) | HAT | No HAT features,  HAT features (ACFP weights can be selected) | Preferences, subjective results (workload, SA) | HAT features were preferred and rated as supportive |
| Strybel et al. (2017) | Workload, eye-gaze durations | Workload was lower in the HAT condition decreasing with time; the uplink of a flight plan needed longer |
| Cover, Reichlen, Matessa, and Schnell (2018) | Integration of HAT tool as EFB into a SPO’s flight deck (Boeing 737 simulator) | HAT at EFB in SPO | Presence of HAT (2); severity of off-nominal events (3) | Subjective pilot preferences, feedback and improvements | Preference for HAT software tool suite and procedures |
| Strybel et al. (2018) | Eye gaze, workload (NASA-TLX); SA (SART) | HAT/No HAT: No differences in workload, SA, time to resolve off-nominal events |
| Summaries regarding HAT in RCO | | | | | |
| Ho et al. (2017) | Description of applying HAT to RCO’s ACFP | HAT | Description applying HAT | The design of a HAT team agent in RCO is described and how it aims to improve teamwork between human and automation | |
| Battiste et al. (2018) | HAT implementation and studies to support RCO | HAT | Summary of 4 experiments | A detailed description of how the method of HAT was applied to the ACFP | |
| Matessa et al. (2018) | Use of distributed simulation to describe application of HAT in RCO | HAT review | Summary |  | |
| Vu, Lachter, Battiste, and Strybel (2018) | NASA ConOps studies for RCO | Review | – | A comprehensive review focused on NASA’s research efforts in RCO. In general, RCO are estimated as a viable ConOps. | |
| Study series: Quantifying pilot contribution to flight safety | | | | | |
| Etherington, Kramer, Bailey, Kennedy, and Stephens (2016) | Rudder trim runway | Experimental simulation (B737-800 simulator) | Crew complement (MCO, RCO due to break, SPO);  Scenario (2 normal, 6 non-normal) | Flight performance;  Eye-gaze;  Failure handling,  Workload (HR, NASA-TLX);  CRM;  Decision making (flight planning);  Perceived safety of flight;  Time to troubleshoot (checklist usage) | Fivefold increase of troubleshoot time, workload increased to unacceptable levels, flight safety was compromised |
| Etherington, Kramer, Kennedy, Bailey, and Last (2017) | Dual Generator Failure | Lasting degraded approach and landing performance, longer time to diversion decision, weather check in both RCO compared to MCO |
| Etherington, Kramer, Bailey, and Kennedy (2017) | In-flight airspeed failure | Double time to conduct checklist for SPO than for MCO |
| Kramer, Etherington, Bailey, and Kennedy (2017) | Hydraulic system failure | Threefold increase of troubleshoot time in SPO, flight safety was compromised, loss of state awareness in high workload |
| Kramer, Etherington, Last, Kennedy, and Bailey (2017) | Drive shaft failure | Flight safety was unacceptable in SPO |
| Bailey et al. (2017); Ho et al. (2017) | Summary and integration of results into context of RCO and SPO | Review of all studies | Simulation studies of 6 aircraft technical failures | Increases in workload for SPO compared to MCO;  Subjective perceived flight safety degraded in SPO and RCO;  Pilots solved failure mode effects in all crew conditions | |
| Faulhaber (2019) | An extension of the workload quantification to other off-nominal scenarios | Experimental simulation | Crew (MCO/RCO), scenario (baseline, turbulence, abnormal) | Flight performance data, workload (NASA-TLX) | Workload differed between crewing only in turbulence and abnormal scenarios. |
| Boy (2015) | A high-level cognitive function analysis of RCO | Function analysis (Boy, 2011) | – | Distinction between classical evolutionary approach and revolutionary approach for RCO; suggestion of an high-level ATM/piloting workstation | |
| Cummings, Stimpson, and Clamann (2016) | Functional requirements for on-board automation in RCO investigated | Interview method | – | List of functionalities and capabilities of an on-board information system | |
| Stimpson, Ryan, and Cummings (2016) | Discrete event simulation model of SPO with advanced autonomy | Computational simulation | SPO with(out) automation; nominal and off-nominal mission scenarios | The single-pilot requires additional assistance by advanced autonomy during periods of high-workload | |
| Lim, Bassien-Capsa, Ramasamy, Liu, and Sabatini (2017) | The introduction of a certifiable virtual pilot assistant for SPO | Review | – | Critical review of current certification and regulations considerable for SPO; a pathway to the certification for commercial SPO | |
| Moehle and Clauss (2015) | Framework for a SPO flight deck system for Part 121 cargo operations | Concept | – | Inclusion of wearable devices to assist the single-pilot with flight deck duties | |
| Schutte (2017) | A review as high-level task analysis of the pilots’ role | Task analysis | Literature, operation materials | A task list for SPO Part 121 operations based on an MCO flight from gate to gate including non-normal scenarios | |
| Benitez, del Corte Valiente, and Lanzi (2018) | Review of ACROSS project | Project review | 4 crewing options for current MCO including RCO | 6 ACROSS pillars, an operational overview over integrated concepts and technologies to handle peak workload and incapacitation of one or both pilots | |
| Neis, Klingauf, and Schiefele (2018); Sprengart, Neis, and Schiefele (2018) | A discussion of RCO and the role of the human ground operator | Opinion | Selected literature | These contributions discussed RCO without achieving a balanced review of the literature. They discuss piecemeal and single issues of RCO. The selection of literature seems randomly. | |
| Reitsma, van Passen, and Mulder (2019) | Concept for a mission planner for the single-pilot | Usability walk-through | Scenario (hydraulic failure; generator drive failure) | Static conceptual pictures of the whole flight deck were presented. The current concept was evaluated as insufficient for flexibility in issues during the course of flight planning. | |
| Tran, Behrend, Fünning, and Arango (2018) | Microsoft HoloLens as alert device for the single-pilot during a fire of 1 engine | Flight simulation | HoloLens (available/not) | Shut down of right engine; reaction time; qualitative feedback | All pilots deactivated the right engine and reacted faster; overlaying of elements could not be prevented |

*Notes*. ACFP = Autonomous Constrained Flight Planner; CRM = Crew Resource Management; CWA = Cognitive Work Analysis (Stanton, Salmon, Walker, & Jenkins, 2017); EAST = Event Analysis of Systemic Teamwork (Jenkins, Salmon, & Walker, 2008; Stanton, Salmon, & Walker, 2018); GS = Ground Station; HAT= Human-Autonomy Teaming (Shively et al., 2017); HR = Heart Rate; HTA = Hierarchical Task Analysis; MCO = Multi-Crew Operations; NASA-TLX = NASA Task Load Index (Hart, 2006); OESD = Operational Event Sequence Diagrams; SA = Situation Awareness (Stanton, Salmon, Walker, Salas, et al., 2017); SART = Situation Awareness Rating Technique (Taylor, 1990); SNA = Social Network Analysis (Wasserman & Faust, 1994); STAMP = System-Theoretic Accident Modelling and Process (Leveson, 2004); STPA = System-Theoretic Process Analysis (Leveson, 2011); VLJ = Very Light Jet; WDA = Work Domain Analysis. Only were indicated, standard measurement methods were applied.

a Johnson et al. (2012); Lachter, Brandt, et al. (2014).

The main operational challenge in designing the Ground Station (GS) is to define the roles and undertake function allocation of the operators on airside and groundside whilst also optimising workload for all personnel. The empirical studies on RCO are definable regarding their research topics. Whilst the re-design of the single-pilot cockpit has often been neglected in most research efforts (Reitsma et al., 2019) the operations of a remote-copilot at a monitor-based GS has dominated (Vu et al., 2018). The physical GS setup has not been elaborated upon despite the fact that it provides more opportunities for different sorts of configurations. The task of the remote, ground-based operator has been formally divided into two main categories. They either support multiple aircraft in rerouting or support one dedicated single-piloted aircraft in a high workload situation. Only the NASA ConOps integrated both types of support and analysed them empirically (Lachter et al., 2017; Vu et al., 2018).

For support of one single-piloted aircraft at a time, several suggestions have been made to ease distributed work at the GS. In NASA’s ConOps, different collaboration tools that indicated visually responsibility and managed acknowledgements, such as a video feedback, shared charts, and an optionally shared view of a flight planning tool did not affect workload but were preferred by the pilots (Lachter, Brandt, et al., 2014; Ligda et al., 2015). A flight-phase-dependent harbour pilot concept has also been investigated further (Koltz et al., 2015). In this, a remote pilot assists the single-pilot in navigating the plane through a specific terminal area airspace during normal departure, arrival, and taxiing phases (further specified in: Schmid, Korn, & Stanton, 2019). The ‘harbour pilot’ offers expertise knowledge in environmental conditions of the airport, such as weather and related procedures as arrival routes to support location-specific activities, including the communication with Air Traffic Control (ATC). A remote-copilot either as PF or PM could be able to undertake 4–6 normal approaches successively, as the workload was rated as low (Koltz et al., 2015). Formal modelling of the function allocation confirm these findings and illustrates the roles and responsibilities in detail (Schmid, Korn, & Stanton, 2019; Stanton et al., 2016). During cruise, the single-pilot would fly the aircraft and receive specific support only when the same requests it. Of course, depending on flight duration this configuration can create further social issues regarding boredom on the airside (Schmid & Stanton, 2019a). In general, this ConOps of *dedicated support* represents a stand-alone approach to RCO, whilst it can also be combined with a ConOps for *multi-aircraft support*.

This type of ConOps merges performing conventional dispatch functions with a “super-dispatcher” flight planning function (Bilimoria et al., 2014). The current flight-following function is enhanced by active decision-making support and rerouting in normal and off-nominal situations. For this purpose, the GS of NASA’s ConOps was improved by including the Autonomous Constrained Flight Planner (ACFP) based on the rationale of Human Autonomy Teaming (HAT; Shively et al., 2017). The ACFP is a tablet-based rerouting and divert system including electronic checklists that was installed in a MCO’s cockpit high-fidelity simulator and the GS for RCO simulations. Additional HAT features enabled to adapt the criteria on which recommendations were made for diversions connected with indicating why they were made. Different off-nominal situations (e.g. weather, medical emergency) required rerouting. Single-pilots preferred HAT features on-board despite no differences in actual workload, SA, and time to resolve off-nominal events. The remote dispatchers and remote pilots preferred HAT features as well which were related to lower workload. In sum, HAT features improved rerouting procedures (including the ACFP) which is encouraging for the future of RCO.

Similar results in comparable rerouting situations were found for the remote super-dispatcher’s functions of this *multi-aircraft support*. The remote operator performed the usual dispatch functions of multiple aircraft under normal conditions in the NASA ConOps. In case of off-nominal events, such as poor weather conditions, the single-pilot could request further assistance from the remote super-dispatcher who would, if the situation dictated it, divert to an alternate airport. No differences in workload and SA were found, although pilots preferred RCO (Brandt et al., 2017; Strybel et al., 2017). Several extensive reviews have discussed and debated the main results of this specific setup elsewhere (Ho et al., 2017; Strybel et al., 2018) which is why only the basic results and corresponding implications for RCO are presented in this paper.

The inclusion of the dispatcher into ground-based support integrates his role into RCO. The dispatcher and the captain are jointly responsible for flight planning activities, the dispatch, and monitoring of the flight progress (which is why the dispatcher assists in rerouting: Berry & Pace, 2011; Smith et al., 1996). Thus, it is anticipated that the dispatcher would be located in the Airline Operations Centre (AOC), employed by the airline and require a specific licence. Relatively little research effort has been expended on the integration of the dispatcher’s software tools into the dynamic nature of the flight planning task (Garland et al., 1999). For example, each tool processes different data and creates (sometimes graphical) representations separately (Munro & Mogford, 2018). Therefore, evolving the dispatcher’s task and software tools together with RCO concepts further could improve this integration.

In general, the empirical human-in-the-loop simulations used to measure operator, team and system performance in RCO has not been undertaken in a consistent manner, which makes cross-comparisons difficult (Table 2). This is especially true for standard workload measurement (Young et al., 2015) and SA is rarely considered by using recommended standard measures (Stanton, Salmon, Walker, Salas, et al., 2017). Until now, no ConOps for RCO has shown to be superior to MCO in terms of workload. Many individual subjective measurements for workload, as well as for SA, were often constructed irrespectively of their standards in quality and comparability (Stanton & Young, 1999). Improvements in methodology are urgently needed.

Similarly, only a narrow range of off-nominal and emergency situations has been considered empirically (e.g. such as bad weather: Brandt et al., 2015). Generally, the more complex emergencies that are especially relevant to RCO tend to be neglected. The recovery from an off-nominal event deviates in procedures and automation involvement from current practices because of the high-workload on-board or the complete loss of the airside-pilot function. Initial theoretical efforts in systems thinking in ergonomics have approached events such as rapid decompression (Revell et al., 2019) and pilot incapacitation (Schmid & Stanton, 2019b). Accordingly, empirical research would benefit from turning toward including such events to specify requirements for future procedure and interfaces development.

Furthermore, all ConOps have not defined explicitly how authority is distributed in the finite options of delegation as it has been indicated by Driscoll, Roy, and Ponchak (2017). Most have simply assumed that command and control remains with the captain until they hand it over to another. Clearer definitions of authority and formalities regarding hand-over control need to be integrated into empirical considerations for each of the ConOps. This issue needs to be resolved (Lachter, Brandt, et al., 2014).

Thus, the flight deck, a GS, as well as operations and procedures need to be designed from scratch, to accommodate the new requirements for effective function allocation. Current flight operations can serve as a realistic initial base on which situations, system operations and abnormalities are likely to be encountered (Schmid, Korn, & Stanton, 2019; Stanton et al., 2016). In general, the ConOps of *dedicated support* as a stand-alone solution for possible future RCO requires more empirical research. The optional combination with *multi-aircraft support* seems realistic but remained less well understood due to less research into the dispatching function. In general, improving and upgrading the dispatcher’s function seems viable (Vu et al., 2018). The overall organization of work and training of these remote operators has been indicated (Bilimoria et al., 2014; Schmid & Stanton, 2019c). An apprenticeship-style-training in new single-pilot specific procedures in a special training fleet would enable pilots transitioning from MCO to RCO in an orderly manner. Nonetheless, these are early considerations of training issues for the conceptual design stages.

Finally, the entire nature of remote work and the lost redundancy of the second pilot must be addressed further in the design of advanced automation support tools. Since a new aircraft models would have to developed specifically for RCO (Driscoll, Roy, & Ponchak, 2017) re-conceptualizing the design of the flight deck and the role of the pilot would need to include such tools.

# Automation Issues: Dealing with the Lost Redundancy of the Copilot

The need for prospective new advanced aircraft automation systems is a necessary requirement for the development of RCO (Comerford et al., 2013; Harris, 2007; Schmid & Stanton, 2019b; Vu et al., 2018). In some situations, the lost redundancy of a second pilot must be compensated by allocating the affected functions to the ground pilot and/or aircraft automation. For example, in the case of pilot incapacitation, an attempt for misuse of the single-piloted aircraft on airside, and a complete loss of the data-link in RCO require additional new automation to detect, classify and react to maintain aircraft safety (Schmid & Stanton, 2019b). An alert or hand-over of control initiated by these advanced automation systems to either ground or airside follows the detection and categorization of a critical event. The current level of technology is claimed to be ready to be applied to RCO for these purposes (Harris, 2007). Nonetheless, less specific research efforts have been made to elaborate and validate this claim regarding RCO. Hence, we review the most relevant developments on how possible technologies could be integrated into the flight deck in RCO to detect incapacitation, system failures, and how to manage responses, such as an autonomous take-over of control in order to land the aircraft safely.

## Pilot Health Monitoring

A ‘so-called’ pilot health monitoring system aims to detect suspicious physiological states of the single-pilot because they can cause higher workload and a complete loss of this function. Most ConOps described previously assume such a system being employed in future but no empirical study has specifically included the issue of pilot health monitoring into RCO. Only theoretical accident models specified its functions in connection with flight operations further by applying a dual-gradation to alert the remote-copilot to either support or take-over control depending on the single-pilot’s health state (Schmid & Stanton, 2019b).

Health monitoring must detect pilot incapacitation reliably because an incident based on a reduction in single-pilot health severely jeopardizes flight safety. The absent redundancy of a second pilot has increased the criticality of incapacitation for safety compared to MCO. Therefore, a system is required that assesses and processes physiological data of a pilot in manned aviation reliably and validly by, preferably, passive and non-intrusive measures. Intrusive and removable measures were considered impracticable, because they are easy to remove and less likely to be accepted by pilots. We excluded operator health monitoring systems from other domains because the monitoring function does not necessarily transfer from one operational environment to another (Caldwell et al., 2009) as in case of the non-invasive drowsiness detection system PERCLOS (Mallis et al., 2000; Mallis et al., 2004).

In the context of manned aviation, the existing monitoring systems (Table 3) can be sorted into two types according to their functional purpose of processing the collected data. Bare pilot health monitoring systems assess the physiological state and alert in case of a deviation of his condition from standard values whereas a so-called electronic crew member additionally process the physiological data to adapt information on interfaces dynamically (Onken & Schulte, 2010). The latter one seems to be unlikely to receive a certification for real flight in the foreseeable future because they are heavily dependent on an assessment of physiological data that are unreliable. In fact, recent developments of simple physiological state assessment tools for aviation only show a medium quality in assessment of the data independent from system. In future, such systems with an increased reliability could alert the remote-copilot on a decrease in physiological health of the single-pilot. In this way, the whole system of RCO could react to an off-nominal event. Schmid and Stanton (2019b) discuss the issues that evolve from the current lack of reliability of a pilot health monitoring system in connection with the consequences on safety of flight operations. The interested reader is referred to the relevant publication.

In sum, there are a wide variety of different systems and applications in aviation of which none was specifically developed for RCO. Their consequences of an application on operator and system performance parameters during such flights remain unknown. Their current state of development is with a very few exceptions not mature for safe flight operations yet. Furthermore, a monitoring system has to measure pilot health in preferably a non-intrusive and passive way. Besides, only a non-intrusive system fixed on the flight deck or providing an alert in case of removal could be applicable to flight practice. In general, the area of assessing pilot health is emerging and we expect many improvements in the future.

Table 3. Passive and non-intrusive and approaches to pilot health monitoring sorted by type of system.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Device and sensors** | **Concept of Measurement** | **Data Processing** | **Quality of assessment** | **State of System’s Validation** | **Name of System (Reference)** |
| Helmet-mounted device (HR, EDA, EEG, EMG, EOG, RR, body temperature)a | Pilot’s physiological and cognitive states | Assessment of workload as part of “operator state”; machine-learning database for each pilot; forwards data to adapt interfaces | – | Prototype was built and successfully demonstrated; empirical testing and validation was planned | Cognition Monitor (COGMON; Pleydell-Pearce, Dickinson, & Whitecross, 2000) as part of the Cognitive Cockpit programme (COGPIT; Bonner, Taylor, Fletcher, & Miller, 2000; Taylor, Abdi, Dru-Drury, & Bonner, 2001) |
| fNIRS: optical brain imaging head-band | Mental workload | Classification of low, medium and high levels | 91% (classification accuracy);  68% (evaluation against expected workload states) | Experimental flight simulation (A320; *N* = 8) | *Crew Monitoring System* CMS (ACROSS Consortium, 2016b; Çakır, Vural, Koç, & Toktaş, 2016) |
| On-line passive fNIRS-based brain computer interface | Working memory load | Discrimination of two levels of working memory load | > 76% (classification accuracy) | Flight simulation vs. real flight (*N* = 28; between-subject) | On-line passive fNIRS-based brain computer interface (Gateau, Ayaz, & Dehais, 2018) |
| Integration of two fNIRS-based complimentary estimators | (1) Pilot’s instantaneous mental state; (2) Online SVM-based classifier | (1) Not-on-task vs. on-task; (2) Working memory load (low vs. high) representing task difficulty | (1) 62% global accuracy, 58% specificity, 72% sensitivity; (2) 80% classification accuracy, 72% specificity, 89% sensitivity | Recall of air traffic control instructions during flight simulation (*N* = 19) | On-line fNIRS-based inference system that integrates two complementary  estimators (Gateau, Durantin, Lancelot, Scannella, & Dehais, 2015) |
| Highly wearable wire­less wristband (PVDF-TrFE pressure sensor) | Reactivity of pilot (various measures) | Force sensitive resistor FSR sensors to discriminate gesture | Assessment of reactivity of pilot with a 90% reliability | Validation in different conditions of fatigue (*N* = 10) without aviation simulation | Highly wearable wireless wristband (Maiolo, Maita, Castiello, Minotti, & Pecora, 2017) |
| Glasses (Infrared re­flectance oculography) | Fatigue | Johns Drowsiness Scale (JDS) to warn in case of drowsiness | Reliability in aviation context is unknown; no validity evaluation | Potential as a prospective re­liable online device | Optalert® (Corbett, 2009) |
| Unspecified (e.g. HR, EEG, RR, blink rate) | Pilot’s health and alertness | Alert when crew and dispatch health/alertness is unsatisfactory; automatic activation of auto-descent | – | US Patent (Grant) | Emergency Descent System monitoring pilot’s health (Aimar, 2010) |
| Wearable device (sensors for: blood oxygen level, HR etc.) | Physiological health data | Wireless transmission to on-board data recording system; possible routes to off-board destinations (e.g. GS, ATC); alerts and information | – | US Patent (Grant) | Pilot Health Monitoring and Hypoxia Prevention System and Method (Serovy & Sitter, 2017) |
| Smart Shirt (HR; RR), cockpit camera, eye-tracking remote, neural activity (fNRIS) | Fatigue, stress, attention, mental workload | Modifies task allocation i.e. information on adaptive interfaces; adaptive alerting. | Degradation in data acquisition (extent typically 5% to 30%) assumed but not evaluated empirically | Representative numerical simulation tests as preliminary validation, certifiable system architectures | *Virtual pilot assistant with Cognitive Pilot Aircraft Interface* (CPAI; Lim, Bassien-Capsa, et al., 2017; Lim, Ramasamy, Gardi, & Sabatini, 2017; J. Liu, Gardi, Ramasamy, Lim, & Sabatini, 2016) |
| Seat belt (Oximetry sensors) | Cerebral peripheral oximeter, cor­poral temperature | Processes data with environmental parameters | – | Test-bed in glider, evaluated during flights; no interferences with other systems | Wireless Sensor Network (WSN) solution (Oliveira, Rodrigues, Mação, Nicolau, & Zhou, 2012) |

*Notes*. BP = Blood Pressure; ECG = Electrocardiogram; EDA = Electrodermal Activity; EEG = Electroencephalogram; EMG = Electromyogram; EOG = Electrooculogram; fNRIS = functional Near-Infrared Spectroscopy; GS = Ground Station; HR = Heart Rate; RR = Respiratory Rate; SVM = Support Vector Machine.

## Aircraft Systems Monitoring

In contrast, the systems to monitor aircraft system behaviour for unsafe operations are far more mature and have been validated in flight simulation studies (Table 4). Such systems aim to detect suspicious behaviour in command and control of the aircraft which can jeopardize flight safety no matter if intentionally caused or not as e.g. a pilot homicide-suicide or an attempt to hijack the aircraft. Different technologies to detect and resolve such events have already been developed under projects funded by the EU. Table 4 represents the single systems that detect suspicious behaviour and provide a strategy together with contributing subsystems that would land the aircraft safely at an adjacent airport. By extension, they protect the aircraft from unsafe operations.

Table 4. Passive and non-intrusive and approaches to systems monitoring.

|  |  |  |
| --- | --- | --- |
| **System** | **Function** | **Reference** |
| Passivation system | On-board system passivates avionics system and lands aircraft safely at an airport | Project PATIN (Schmitt, Többen, & Philippens, 2010) |
| On-board Threat Detection System (OTDS) | Detects dangerous objects, suspicious human activity and unauthorized access from aircraft systems and several kinds of sensors; alerts the cockpit crew | EU-project SAFEE (Gaultier & SAFEE Consortium, 2008; Laviv & Speijker, 2007) |
| Threat Assessment and Response Management System (TARMS) | Surpass of trigger level: information/alert to crew, recommendation of possible response; can conclude that cockpit crew is no longer in control … |
| Emergency Avoidance System (EAS) | … TARMS initiates protecting flight path by automated manoeuvres. Hence, EAS disables all unauthorized inputs to flight controls and aircraft systems. |
| Flight Reconfiguration Function (FRF) | Automated landing at secure airport of both pilots did not regain control over the aircraft | SOFIA (Bueno, Herrería, & Consortium, 2010) |
| Emergency Aircraft Control System (EACS) | Triggered by CMS; emergency system; capability to control and land aircraft, authorized and executed by Flight Warning System | EU-project ACROSS (ACROSS Consortium, 2016a; Benitez et al., 2018) |
| Electronic Stand-by-Pilot (ESP) | On-board system: Emergency stabilization, safe continued flight, approach and landing of CS25-type aircraft; ground strategic control and assistance possible via data-link |

*Notes*. CMS = Crew Monitoring System.  
Project abbreviations: ACROSS = Advanced Cockpit for Reduction of Stress and Workload; PATIN = Protection of Air Transport and INfrastructure; SAFEE = Security of Aircraft in the Future European Environment; SOFIA = Safe autOmatic FlIght back and landing of Aircraft.

Although all of these systems at current state-of-the-art were developed for MCO they could be transferred and applied to RCO to fulfil the same purposes. In general, their state of development is promising for further system integration. This represents a viable next step in research as shown by a study modelling the functions related to RCO (Schmid & Stanton, 2019b).

## Take-over and Hand-back of Control

These advanced monitoring systems can create “control hand-back problems” with ground-based support resulting from the affected pilot being out of the loop (Endsley & Kiris, 1995). The pilot needs time to get to the controls and to regain SA, which may be accompanied by a cognitive delay (e.g. Eriksson & Stanton, 2017). Recovery time can be even longer if a more extensive systems diagnosis is required in off-nominal and emergency situations (e.g. Stanton & Baber, 2008). Procedures have to define and clarify the circumstances of a take-over of control. Relatedly, an authority distribution has to be predefined for the reduced-crew ConOps (Driscoll, Roy, & Ponchak, 2017).

More particularly, the single-pilot can be pilot-in-command whilst the remote-copilot can fulfil different operational functions. The remote-copilot can be optionally available as a standby redundancy or actively act as second pilot. If the single-pilot is on standby due to undertaking activities such as eating, lavatory, napping, making logbook entries, or being out of the cockpit, then the remote-copilot becomes pilot-in-command. Furthermore, the single-pilot can become incapacitated, in which case the authority over of the flight would automatically be transferred to the remote-copilot. Finally, the paradox remains that both of the pilots could act in an adversary or suicidal way which would disrupt flight safety. In this case, a second GS providing ground redundancy could serve a distinct larger number of ground support units to back-up this extremely rare case of an emergency. All these examples require a definition when and how control is transferred to ground and back by either the single-pilot, the remote-copilot, or even by advanced automation.

In research, only a few aspects of transferring control in RCO have been assessed. For example, a lack of previous knowledge on aircraft status and environment is not necessarily detrimental to SA as it can be provided to a remote-copilot upon need for immediate assistance in rerouting (Brandt et al., 2015). It is likely that there is no SA decrement after an additional transfer of control to the remote-operator in rerouting when he is provided with environmental and system data of the concerned aircraft. The collaboration tools of the same GS setup can support making authority distribution transparent (Lachter, Brandt, et al., 2014; Ligda et al., 2015). It is unknown if these results are transferable to emergency situations, which are by their nature, much more complex in operations. An integration of advanced monitoring systems into RCO would inevitably lead to investigating the issues of transfer of command and control further.

# Pilot Incapacitation: Recovering from an Airside Loss of Control

Pilot incapacitation as the main hurdle for RCO has received surprisingly little attention in research (Johnson et al., 2012; Stanton et al., 2016) whereas the countermeasures in MCO are firmly established and well-regulated (Schmid et al., 2018). There is only one predictive accident model that has been reported in the open literature for RCO (Schmid & Stanton, 2019b). More research is required on how procedures could be developed and adapted to tackle pilot incapacitation.

Consequently, remote piloting gains in importance for the remote-copilot when they assume the role of the active pilot. Similar functions have already been investigated for operators of Unmanned Aerial Vehicles (UAVs). They usually operate one or multiple UAVs to conduct a range of different tasks depending on application of the same (Hobbs & Lyall, 2016). Although applications with one UAV weighing more than 55 pounds operate at comparable altitudes of airliners and are airborne similar time periods, the human factors are unique over and above those that apply to conventional flight (Kaliardos & Lyall, 2014). The operator has to control the UAV all the time, manage control links, avoid collisions in absence of an outside view, and might be required to transfer control to another GS during flight operations. In contrast, the single-piloted aircraft must be capable of flying on its own without support and becomes a UAV only for a narrow time period or in an emergency. Thus, aviate, navigate, communicate, and especially ‘manage’ differ when we consider the analyses of these (purpose-related) functions of RCO and UAVs (Hobbs & Lyall, 2016, p. 27; Stanton et al., 2016, p. 335). Some of the technologies used by UAVs have relevance for RCO. Apart from initial considerations of the data-link, no efforts have been made yet to transfer these to RCO (Schmid & Korn, 2018). Finally, UAVs’ technology will become more important at more advanced stage of RCO system development.

# Communication/Social Issues: Facing Boredom

Under all conditions, the communication between both pilot (single and remote) will have to change fundamentally because they are spatially distributed at different work stations. A spatial separation under current conditions was found not to affect the pilots’ decisions on flight planning due in off-nominal events (Lachter, Battiste, et al., 2014). Nevertheless, they generally preferred to sit next to each other. Confusions were apparent in the pilots not being aware of what the other pilot was doing. Different setups of a video feedback were not helpful in this matter whereas collaboration tools prove to be effective in supporting team collaboration (Lachter et al., 2017). These findings were not investigated more in detail although fatigue management has been assumed as being adaptable to all different flight durations in RCO (Schmid & Stanton, 2019a). More research is required on how different periods of collaboration and of operating as single-pilot alone affect workload, SA and especially boredom and vigilance issues under different circumstances. Furthermore, the use of advanced automation must not generate vigilance issues (Warm, Matthews, & Finomore, 2008). It should use attentional resources appropriately to prevent boredom or overload to not degrade system performance.

# Certification Issues: Regulating Operational Practice

Before RCO can be taken from research into practice certification and approval issues have to be taken into account. Currently, initial efforts have been made to identify certification requirements for SPO under 14 C.F.R. Part 121 and Part 125 operations (Wilson et al., 2013). It does mean that several parts of the regulatory certification requirements would have to be changed in future to include SPO/RCO or, at the very least, an equivalent level of safety will have to be demonstrated. For example, the certification test program would need to address the same workload functions as specified in CS 25.1523 and 14 C.F.R. §25.1523 by assessing them in comparison to a certified aircraft (H. Liu, Ma, Zhang, Jin, & Dong, 2017). An example of a virtual pilot assistant, including a psychophysiological monitoring function, shows how a system required for RCO can be considered for certification (Lim, Bassien-Capsa, et al., 2017). In general, it seems possible to overcome many of the certification challenges in future. Until then, all the other research issues, as discussed previously, need to be solved.

In contrast, the data-link technology would need to be certified from the ground up. It must provide a sufficient safe and reliable high-bandwidth data-link to be able to provide ground support (Driscoll, Roy, Ponchak, & Downey, 2017). In this way, information is transferred between air and ground. Cyber-safety and security of the data-link has been rarely addressed in connection to RCO although it has been recognized as an essential issue (Comerford et al., 2013). For example, a secure air/ground data-link was already developed to protect communications limited to a smaller amount of transportable data (Laviv & Speijker, 2007). In contrast, RCO will have to manage a larger quantity of data.

The UAVs’ Control and Non-Payload Communication (CNPC) links represent a possible technological base (Yong, Zhang, & Joon Lim, 2016). CNPC links are characterized by high reliability, low latency and security under low data rate requirements. UAVs communicate via them safety critical information like command and control signals, aircraft status data, sense and avoid information, as well as ATC related information. Securing this communication in RCO requires a cryptographic key management infrastructure (Driscoll, Roy, & Ponchak, 2017). It is unknown if the current Heavyweight Public Key Infrastructure (PKI) for data communication of aircraft can be used for RCO because the cryptographic latency problem limits its applicability. Consequently, the use of a special hardware encryption has to be combined with a wide bandwidth to keep a low latency and high-speed link. This is why manual control seems unlikely remotely. In addition, signals relayed beyond line of sight transmission can delay responses and shortly disrupt the data-link. In this case, a single-piloted aircraft could be equipped with a supervisory mission management monitoring the link’s quality and applying graded solutions dependent from type of failure (Schmid, Korn, Wies, et al., 2019). Examples are similar to applications in the UAVs autoland system at a safe base (Mouloua, Gilson, Daskarolis-Kring, Kring, & Hancock, 2001). This technology will be critical to keep RCO resilient against any off-nominal events (Schmid & Korn, 2018). Further progress in research regarding RCO and the required data-link technology certification issues will play an important role in the mid- and long-term future.

# Conclusions

The different ConOps and related studies in place confirm that RCO are viable in future. They considered the different requirements for function allocation by applying various methods but agree in their main characteristic of ground-based support. Next, premature technology to monitor pilot health as well as more mature technology to monitor system states and to land an aircraft autonomously at an alternate airport exists but has not been integrated into RCO research yet. Here, an integration of the available technology could foster investigating pilot incapacitation as well as communication and social issues more in detail which is required to anticipate possible operational issues in all aspects. In both areas, research lags current efforts. The required infrastructure of a low latency, high bandwidth, secure encrypted and highly reliable data-link via satellite does not exist yet. Other issues of RCO have not been investigated in depth but debated already. Among these are possible changes in selection and training of the operators, the design of the single-pilot flight deck, legal issues such as accountability, teamwork and SRM, the application of RCO to different flight durations, and how such operations should be included into current commercial aviation depending on facilities, airlines, fleet size, and technological infrastructure available. Nonetheless, certification in the end remains a challenge but seems achievable.

Last but certainly not least, as technological developments for different aircraft systems continue to evolve several useful applications could be developed to assist the pilot’s functions in different monitoring areas, such as reducing workload in RCO. This does not account solely for the assessment of pilot health but also for aircraft systems monitoring and mission management tools. For example, an aero-conformal ice detection system could serve as base for automated anti-ice system representing a primary reliable ice detector for safe flight in icing conditions in accordance with new FAA and EASA regulations (Richards, 2012). Other advances in technology include automated and integrated checklist systems (Airbus, 2011b), intelligent voice recognition systems and improvements of the communication system (Arthur, Shelton, Prinzel, & Bailey, 2016; Schutte et al., 2007). None of these systems has been investigated in the context of RCO.

Finally, getting industry and public acceptance is essential for further progress toward commercial RCO. Cargo operations have been suggested as a potential use case (Stanton et al., 2016), although most operators make use of aircraft that were previously used for passenger transport. This issue has been apparent at Congress who passed the FAA reauthorization bill in 2017 aiming to establish a state-funded specific research program on SPO for cargo operations. Pilot unions have opposed SPO (Carey, 2018) and in the final bill the research program was taken out (*FAA Reauthorization Act of 2018 (H.R.4)*, 2018; *FAA Reauthorization Act of 2018 (H.R.302)*, 2018). Against this background, research on RCO has to provide a firm base for taking up the topic in industrial context as well. In fact, commercial RCO represents a viable and possible option to address the growing demand for air transport of passengers and freight (Airbus, 2018; Boeing, 2018) as well as the expected pilot shortage over the next 20 years.

# Abbreviations

ACFP Autonomous Constrained Flight Planner

AOC Airline Operations Centre

ATC Air Traffic Control

BP Blood Pressure

CNPC Control and Non-Payload Communication

ConOps Concept of Operations

CMS Crew Monitoring System

CRM Crew Resource Management

CWA Cognitive Work Analysis

EACS Emergency Aircraft Control System

EAS Emergency Avoidance System

EAST Event Analysis of Systemic Teamwork

ECG Electrocardiogram

EDA Electrodermal Activity

EEG Electroencephalogram

EMG Electromyogram

EOG Electrooculogram

ESP Electronic Stand-by-Pilot

FMS Flight Management System

fNRIS functional Near-Infrared Spectroscopy

FRF Flight Reconfiguration Function

GS Ground Station

HAT Human-Autonomy Teaming

HR Heart Rate

HTA Hierarchical Task Analysis

IATA International Air Transport Association

MCO Multi-Crew Operations

NASA-TLX NASA Task Load Index

OESD Operational Event Sequence Diagrams

OTDS On-board Threat Detection System

PF Pilot Flying

PKI Public Key Infrastructure

PM Pilot Monitoring

RCO Reduced-Crew Operations

RR Respiratory Rate

SA Situation Awareness

SART Situation Awareness Rating Technique

SME Subject Matter Expert

SNA Social Network Analysis

SPO Single Pilot Operations

SRM Single-Pilot Resource Management

STAMP System-Theoretic Accident Modelling and Process

STPA System-Theoretic Process Analysis

SVM Support Vector Machine

TARMS Threat Assessment and Response Management System

UAV Unmanned Aerial Vehicles

VLJ Very Light Jets

WDA Work Domain Analysis

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