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Huddlestone, J, Sears, R & Harris, D

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The Use of Operational Event Sequence Diagrams and Work Domain Analysis techniques for the Specification of the Crewing Configuration of a Single Pilot Commercial Aircraft

John Huddlestone*, Rod Sears and Don Harris

Centre for Mobility and Transport Research

Coventry University

Priory Street

Coventry CV1 5FB

United Kingdom

* Author for correspondence

Email: john.huddlestone@coventry.ac.uk

Tel: 02477 657805

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ABSTRACT

Aircraft manufacturers and avionics systems suppliers are developing technologies for airliners that will be operated by just a single crew member. An alternative approach to using a large amount of on-board computing proposes the utilisation of extant technology derived from single seat military aircraft and Uninhabited Air Systems where control is distributed in real time across the aircraft flight deck and ground stations (which supervise several aircraft simultaneously). Using a combination of Operational Event Sequence Diagrams and Work Domain Analysis techniques, the allocation of tasks and requirements for the development of supporting technologies for such an operational architecture are identified in a low visibility taxi scenario. These analyses show that many of the functions undertaken by a second pilot in this situation are associated with checking, surveillance and monitoring activities. These must be undertaken either by automated aircraft systems or the monitoring personnel in the ground station. This analytical approach can successfully provide the necessary information underpinning the design requirements for such an aircraft concept

Keywords: **A**llocation of function; flight deck design; reduced crewing; work domain analysis; operational event sequence diagrams.

INTRODUCTION

The trend in flight deck design over the past half century has been one of progressive 'de-crewing'. The common flight deck complement is now two pilots, who with much increased levels of assistance from the aircraft accomplish the same tasks once undertaken by five crewmembers in 1950s jet airliners. The modern commercial aircraft and its systems are now largely under supervisory control. Emphasis is placed on the management of the automation and crew, rather than flight path control *per se* (CAA 2013).

Research into the operation of long-haul aircraft, which during the cruise phase will be supervised by just a single member of flight deck crew, is currently underway in the Advanced Cockpit for the Reduction of Stress and Workload (ACROSS) project (see http://www.across-fp7.eu/). However, some aircraft manufacturers and avionics systems suppliers (e.g. Embraer and Honeywell – Keinrath, Vašek & Dorneich, 2010) are developing technology for airliners that will be operated by just a single crew member during all phases of flight. Embraer announced that it was hoping to provide single-pilot capabilities by 2020. The approach commonly adopted focusses on the development of much increased levels of automation (e.g. Intelligent Knowledge-Based Systems and adaptive automation). This method has particularly been applied in the military domain but with only mixed success (e.g. the COGnitive cockPIT – COGPIT programme - Bonner, Taylor, Fletcher & Miller, 2000; Taylor, Howells & Watson, 2000; and the Cockpit Assistant Military Aircraft – CAMA programme - Schulte & Stütz, 2001; Stütz & Schulte, 2001). CASSY (the Cockpit Assistant System) was a civil version of CAMA, developed by the same team (see Onken, 1994; Onken, 1997).

The trend toward increased levels of automation and autonomy is also being observed in road vehicles. Initially, automation in road vehicles was concerned simply with low-level control functions (e.g. automatic gear boxes and basic cruise control) and secondary systems (e.g. self-seeking radios). However, in recent years more advanced automation has been introduced (e.g. adaptive cruise control and lane-keeping systems – see Carsten et al., 2012). These control systems are now being supplemented with in-vehicle autonomy permitting driverless operations. The role of the driver therefore becomes an operator – a setter of high level goals.

An alternative design approach to using a large amount of on-board computing for a single pilot airliner was proposed by Harris (2007). This concept used a distributed systems-based design philosophy utilising extant technology derived from single seater military aircraft and UASs (Unmanned/Uninhabited Aircraft Systems) including ground station design. The control and crewing of the aircraft was distributed in real time across the aircraft flight deck and ground stations, the latter of which supervised several aircraft simultaneously. In this configuration, the second pilot was not *replaced* by high levels of automation; they were *displaced* (see also Harris, Stanton & Starr, 2015 and Stanton, Harris & Starr, 2015). Furthermore, the support from the ground is only provided when required (for example, in times of high workload; when safety-critical cross checking is needed or in emergency situations). This approach has also been adopted by NASA in its development of a single crew aircraft concept (Bilimoria, Johnson & Schutte, 2014; Lachter et al., 2014). This design concept regards a future single crew aircraft as just one part of a wider operating system, a radical change from the operation of current generation airliners. It also avoids the requirement for a great deal of advanced, on-board automation. A similar approach has also been used in a number of military developments utilising both manned and unmanned/uninhabited air vehicles (e.g. Schulte & Meitinger, 2009; Schulte & Meitinger, 2010; Schulte & Meitinger, 2012).

The initial high-level design architecture proposed for operating such a single crew aircraft considered in this paper consists of several discrete elements (Stanton, Harris and Starr, 2014):

- The aircraft itself (including pilot)
- Ground-based component including:
    - 'Second pilot'/'Ground Pilot' (GP) support station/office

- Real-time engineering support
- Navigation/flight planning support.

To make a single crew aircraft economically viable, there must be fewer people employed in ground support roles that would be engaged as second officers. The ratio of personnel on the ground to those on the flight deck has not been finally determined in any of the proposed design configurations. Initially it was proposed that a ground-based 'super-dispatcher' would be responsible for the oversight of up to 20 aircraft during normal operations (Bilimoria, Johnson & Schutte, 2014). However, later goals from NASA have been for the ground-based element to provide support for up to 12 aircraft in flight (Croft, 2015).

The main driver for single pilot operations is financial. Norman (2007) reported in Comerford et al. (2013) suggested that between 2005-25, flight deck crew costs over the service life of an aircraft could be up to $6.8 trillion dollars thereby giving scope for a significant reduction in operating costs if single pilot operations were possible. However, it was also pointed out that considerable technical, safety and operational challenges must first be overcome. Airline personnel costs vary between about 11% of operating costs to nearly 25%, depending upon aircraft type, sector length and how much activity is outsourced (Ryanair, 2009; easyJet, 2013). Annual accounts from a typical low-cost operator show that the crew represent nearly 13% of operating costs (excluding fuel and propulsion – easyJet, 2013). Halving the number of pilots on the flight deck will produced significant cost savings, especially in smaller commercial aircraft operated on shorter routes and 'thinner' (lower volume) routes, which may not be economically viable with higher capacity airliners.

However, there is also another imperative for reducing the number of pilots. Airbus in 2011 estimated that the size of the world's passenger fleet will more than double in number from 14,016 (in 2008) to over 31,000 aircraft in 20 years. The Boeing estimate is considerably higher, suggesting a world-wide fleet of 39,500 aircraft by 2030. At the same time, there are already signs of an increasing shortage of airline pilots. Boeing estimate that between 2015-34, 95,000 commercial pilots will be required in North America alone versus a potential supply of only 64,000 in this period.

Reducing the flight deck crew to just a single pilot means that they require increased assistance, hence the need to allocate work appropriately both between the pilot and the aircraft's automated systems, and the pilot in the aircraft and assistance from the ground. It requires a systematic approach to the allocation of work between the pilot and other systems, bearing in mind that such an allocation of tasks will change flexibly regarding circumstance and flight phase. Such a distribution of functions (or tasks) requires consideration of a range of factors. While technically functions are at higher level of abstraction than tasks and are device independent (Corbridge & Cook, 1997) the terms 'task' and 'function' are often used interchangeably. Deardon, Harrison & Wright (2000) suggested that functions should refer to activities undertaken by whole human-machine systems, whereas tasks refer to an activity involving just the human operator. Furthermore, allocation of function is usually based upon analysis of lower-level tasks.

Operational Event Sequence Diagrams (OESDs) can provide a simple yet rigorous basis upon which the potential allocation of work can be assessed (Harris, Stanton & Starr, 2015). The output of an OESD shows a time-based sequence of tasks, including the interaction between operators and technological artefacts. It graphically depicts task processes, usually developed from an initial task analysis, using a set of standardised symbols. OESDs may be developed from observations, analysis of standard operating procedures and/or interviews (in the case of an existing system) or from a formal analysis of projected task flows (during design stages of a new system). Each task step is represented by a symbol arranged in one of a number of time lines (often referred to as a 'swim lanes'), each dedicated to an individual human or machine agent. The symbols representing tasks are linked by directional arrows.

OESDs were developed by Kurke (1961) as a method for representing operator information decision sequences and complex, multi-person, tasks (Kirwan & Ainsworth, 1992; Sanders & McCormick, 1993). Subsequently, their uses have been extended to include human-machine interaction (Stanton, Salmon, Rafferty, Walker, Baber & Jenkins, 2013). Stanton, Sorensen & Banks (2011) and Harris, Stanton & Starr (2015) used OESDs in a range of scenarios for the analysis of activities on commercial aircraft flight decks. In the latter study, their use was extended to encompass the incorporation of potentially increased levels of automation.

Deutch & Pew (2005) used a Cognitive Work Analysis (CWA) based approach to help define the assistance required for the pilot in a single crewmember aircraft. This analytical approach was predicated upon the notion of providing extensive pilot automated assistance on the flight deck (particularly synthetic vision systems; data linking and direct voice input/output systems). However, it is considered good practice to use a combination of analytical methods to develop a sound understanding of the operation of any system. In the study by Harris, Stanton & Starr (2015) the OESDs were supplemented with a Work Domain Analysis (WDA), one component of a CWA (Rasmussen et al, 1994; Vicente, 1999; Jenkins et al, 2009). Complex socio-technical systems, such as flight operations, are made up of numerous human and non-human interacting parts, which made this multi-method approach more applicable than a simple CWA. In addition to the time- and task-based analyses inherent in the OESDs, WDA serves to identify the constraints that are imposed by the purposive and physical context of operations (Naikar, 2006). WDA is conducted at the functional level, being used to describe the environment within which the activity is conducted. It identifies a fundamental set of constraints on the actions of system components, providing a foundation for subsequent phases of development (McIlroy and Stanton, 2011). The five levels of abstraction in WDA, which are presented diagrammatically in an Abstraction Hierarchy (AH), comprise:

- Functional Purpose: the overall purposes of the system and the external constraints on its operation
- Values and Priority Measures: the criteria the work system uses to measure its progress towards achieving the above functional purposes
- Purpose-Related Functions: the general functions that are necessary for achieving the functional purposes
- Object-Related Processes: the functional capabilities (and limitations) of the physical objects (below) that enable the purpose-related functions, and
- Physical Objects: the objects that afford the object-related processes.

WDA has previously been used successfully in the description of various innovative crewing options for future flight decks (see Stanton, Harris & Starr, 2016).

The following analyses use a combination of OESD and WDA analytical techniques to identify the allocation of tasks and development of new technologies to support the distributed Single Crew Aircraft operational architecture described initially by Harris (2007) and subsequently in Stanton, Harris & Starr (2014) where operation is dispersed across the aircraft itself and a ground-based support component. The use of multiple, complementary Human Factors methods has been shown to increase the sensitivity and comprehensiveness of the analysis of complex systems (e.g. Stanton et al., 2009; Carayon et al., 2015).

The objective of the following analyses is to ensure at the early design stages that the pilot is not overburdened during either the higher workload phases of normal flight, nor during non-normal or emergency situations. However, decision making must also remain in the most appropriate location (flight deck Vs ground) to allow appropriate safe and efficient actions to be taken. As listed in the Boeing Pilot's Manual for the B757-200, '*avoid nonessential conversation during critical phases of flight, particularly during taxi, take-off approach and landing*', it is therefore, essential to concentrate on the task with few distractions from outside the aircraft, (Boeing 2006).

Workload needs to be distributed appropriately between aircraft, ground support roles and the automated systems supporting the pilot. Keinrath, Vašek & Dorneich (2010) suggested that the adaptive automation on board a single crew aircraft had four functions:

- Task scheduling (e.g. direct the pilot to higher priority tasks; defer lower priority tasks or assist in task-switching)
- Modify 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/or
- Promote task sharing (e.g. provide automation assistance on tasks, simplifying the tasks).

It is proposed that these functions can be achieved *a priori* at the design stages by use of appropriate analyses rather than be undertaken dynamically by an AI system, much simplifying the automation required. This approach is further supported by flight crew training and CRM (Crew Resource Management) practices. For example, Boeing recommend *'It is important that all flight deck crewmembers identify and communicate any situation that appears unsafe or out of the ordinary*', (Boeing 2006).

The following analyses are part of larger programme of research covering many flight phases incorporating normal, non-normal and emergency scenarios. These included pre-flight; push-back; take-off and initial climb (including engine failure after take-off); cruise; descent (including emergency descent from altitude); approach and landing (including a go-around). These scenarios are described in Huddlestone (2015).

This paper illustrates the application of OESD and WDA analytical techniques to the taxi-in after landing phase of flight. This is a relatively demanding phase of flight, even though the aircraft is on the ground. The European Aviation Safety Agency (EASA, 2011) recommends that taxi phase should be treated as a critical phase of flight. The importance of this phase is re-enforced by Boeing Crew training (Boeing 2006) which lists 18 priority crew actions whilst taxiing such as; progressively follow the position on the airport diagram; in low visibility call out position and all marker boards; if in doubt regarding the clearance or position—stop; avoid distractions and consider delaying checklists until stopped. Many essential operations to configure the aircraft are required while simultaneously taxiing from the runway to a designated gate (often on an unfamiliar airport) via the approved route, in relatively confined environs. In reduced visibility, this is demanding of two flight deck crew so will be a considerable challenge for single pilot operations, hence its selection for illustrating this analytical approach.

METHOD

The analysis was conducted in two phases. The first phase of the analysis was concerned with capturing how the taxiing task was conducted in two-crew operations, which served as a baseline for further analysis. The OESD method utilises a scenario-based analysis approach (see Deardon, Harrison & Wright, (2000). The OESDs were developed from the required task sequence along with an understanding of how each operation was undertaken and by whom (or what). The role of technological artefacts and their interaction with the pilots was also considered. Task information elicited included such categories as:

- Operations or actions
- Transmission of information
- Receipt of information
- Pilot decisions
- Storage of information or objects

- Delays or periods of inactivity
- Inspections or checks
- Transportation of data, artefacts and material
- Timeline or task sequence

(Stanton, Salmon, Rafferty, Walker, Baber & Jenkins, 2013)

The OESDs were constructed including columns assigned to operators on-board or off-board the aircraft and technological assistance. The method was adapted and extended to accommodate parallel, simultaneous tasks undertaken by several actors and to encompass communication aspects (see Harris, Stanton & Starr, 2015). It was supplemented with symbology depicting communication activities and their content. A complementary AH was then produced. This was developed top-down (following Stanton et al, 2009) first capturing the overall purpose of the system and the value priorities and measures, and then synthesising the detail of the OESD into the purpose related functions, physical functions and physical forms. A table summarising the key attributes of the taxiing task was also produced. A review of these outputs informed the development of a list of issues that would have to be addressed if the task were to be executed successfully in the single pilot context. The second phase of the analysis then focussed on how these issues could be addressed. This was achieved by the complementary revision of the OESD and AH. The key differences between this phase and the first in this phase in the development of the OESD and AH were that:

- The AH was developed by revising the AH developed in the first phase from the bottom up (following Stanton et al, 2009) by considering how new technologies could be exploited to support the taxiing task and how the introduction of these technologies could facilitate the allocation of PNF tasks in the baseline case to the PF, GP support station or aircraft.
- The OESD was adapted to reflect the reallocation of tasks from the PNF and the inclusion of new technologies.

Analysis Scenario

Any multi-crew commercial aircraft must be commanded by an appropriately qualified pilot with the rank of Captain, supported by a First Officer or Co-Pilot. Before each flight sector, the Captain will allocate a pilot to take responsibility for handling the aircraft. This pilot becomes PF (Pilot Flying); the other pilot is designated PNF (Pilot Not Flying sometimes also referred to as Pilot Monitoring - PM) whose role is to monitor the management of the flight; double-check the PF's control actions; and undertake support duties, for example communications and check-list reading. These duties may be undertaken from either seat in modern, two-crew flight decks. PF and PNF is the nomenclature used in the following analyses.

Material for undertaking the OESD and WDA analyses was drawn from several sources, including aircraft operations manuals and Standard Operating Procedures (SOPs). The crew procedures were also aligned to follow good CRM practices, in that '*one of the basic fundamentals is that each crewmember must be able to supplement or act as back up for the other crew member*', (Boeing 2006).

These were complemented by 'walkthrough, talk-through' interviews and structured de-briefs of experienced, qualified Test Pilots and Senior Airline Captains, who also helped to devise the scenarios examined. The scenarios utilised in the analysis of single pilot operations covered all phases of flight and included:

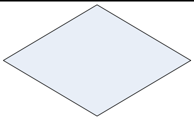
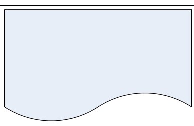
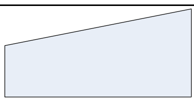
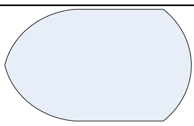
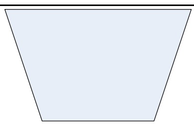
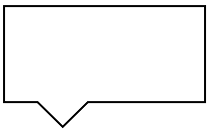
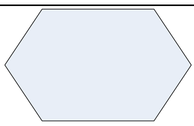
- Normal Actions – actions that must be undertaken during normal operations.
- Significant environmental conditions – that can impact on the conduct of normal operations, such as icing conditions and weather conditions such as reduced visibility.
- Considerations – issues that must be taken into consideration.
- Key Interactions – required to successfully handle the scenario.

RESULTS

Baseline OESD and WDA Analyses

The OESD for the baseline case of taxiing the aircraft to the gate is shown in Figure 1a&b. Table 1 provides the key to the symbols used in figure 1. The corresponding AH developed during the WDA is shown at Figure 2. Table 2 captures key attributes of the taxiing task identified during the analysis.

Table 1 OESD Symbols

	**Process or Task**
	**Decision**
	**Document**
	**Manual input**
	**Display**
	**Manual Operation**
	**Terminator**
	**Connector**
	**Voice Communication**
	**Delay**

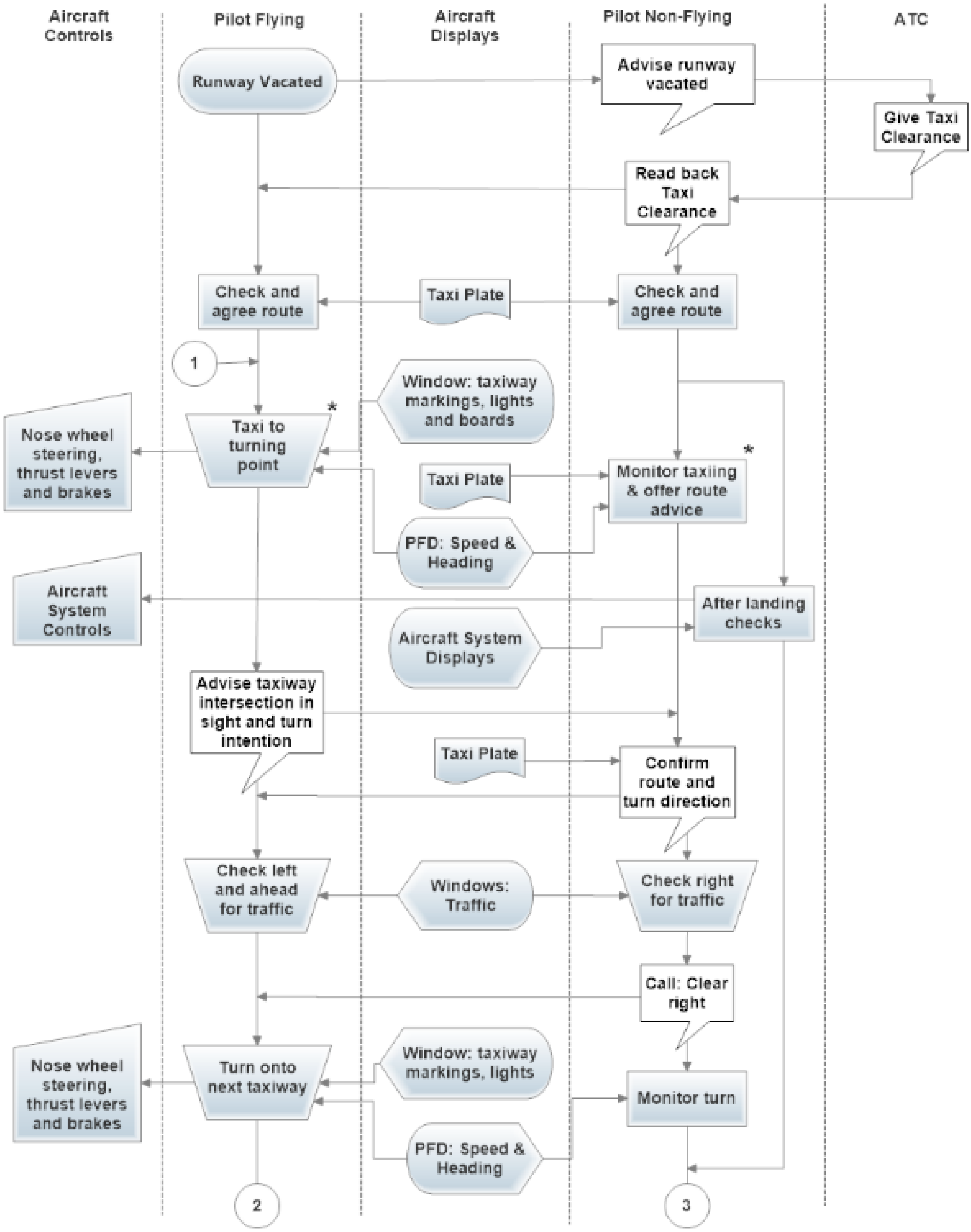


Fig 1a **OESD for taxiing the aircraft to the gate for two pilot operations (baseline)**

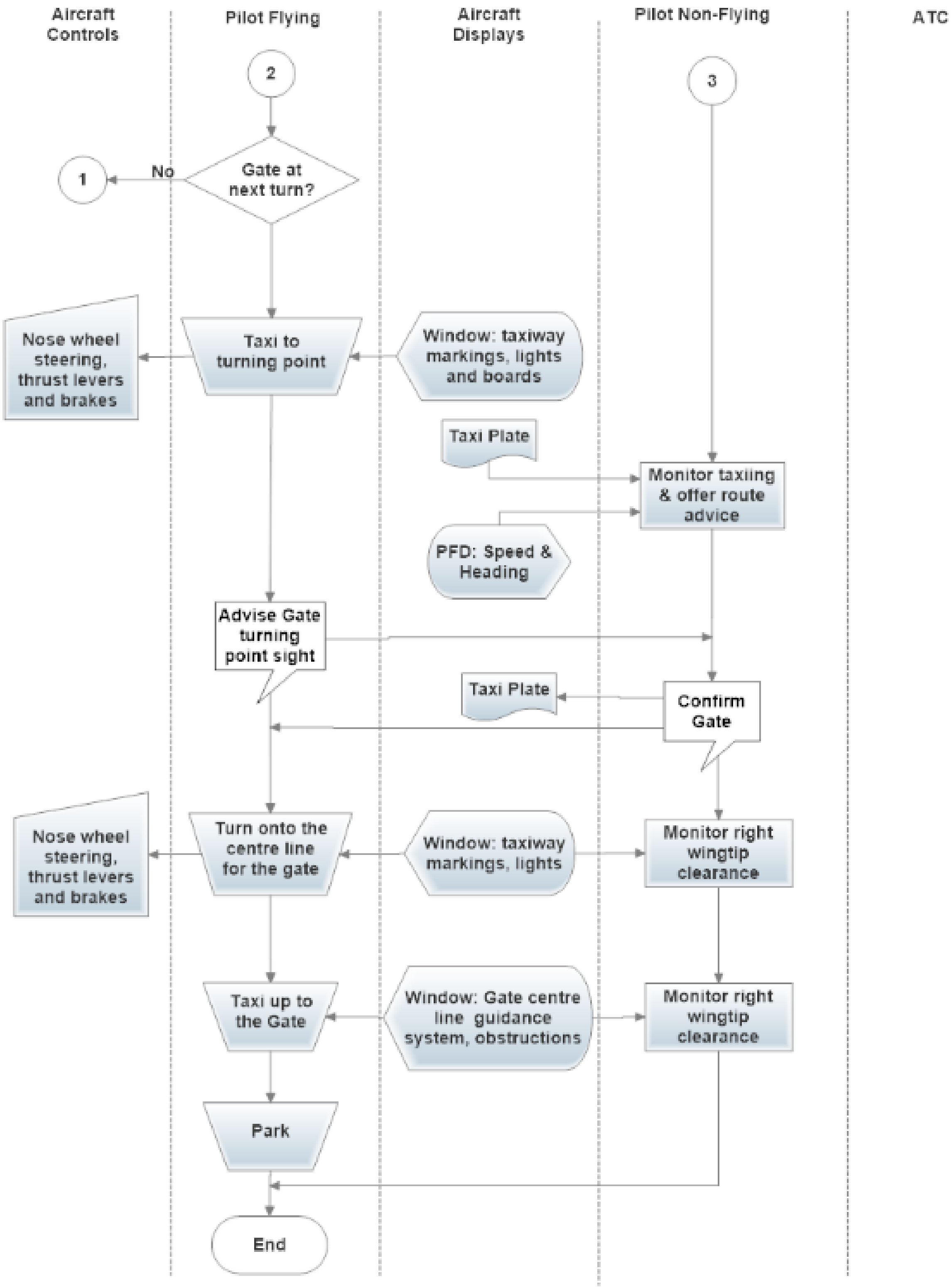


Fig 1b **OESD for taxiing the aircraft to the gate for two pilot operations (continued).**

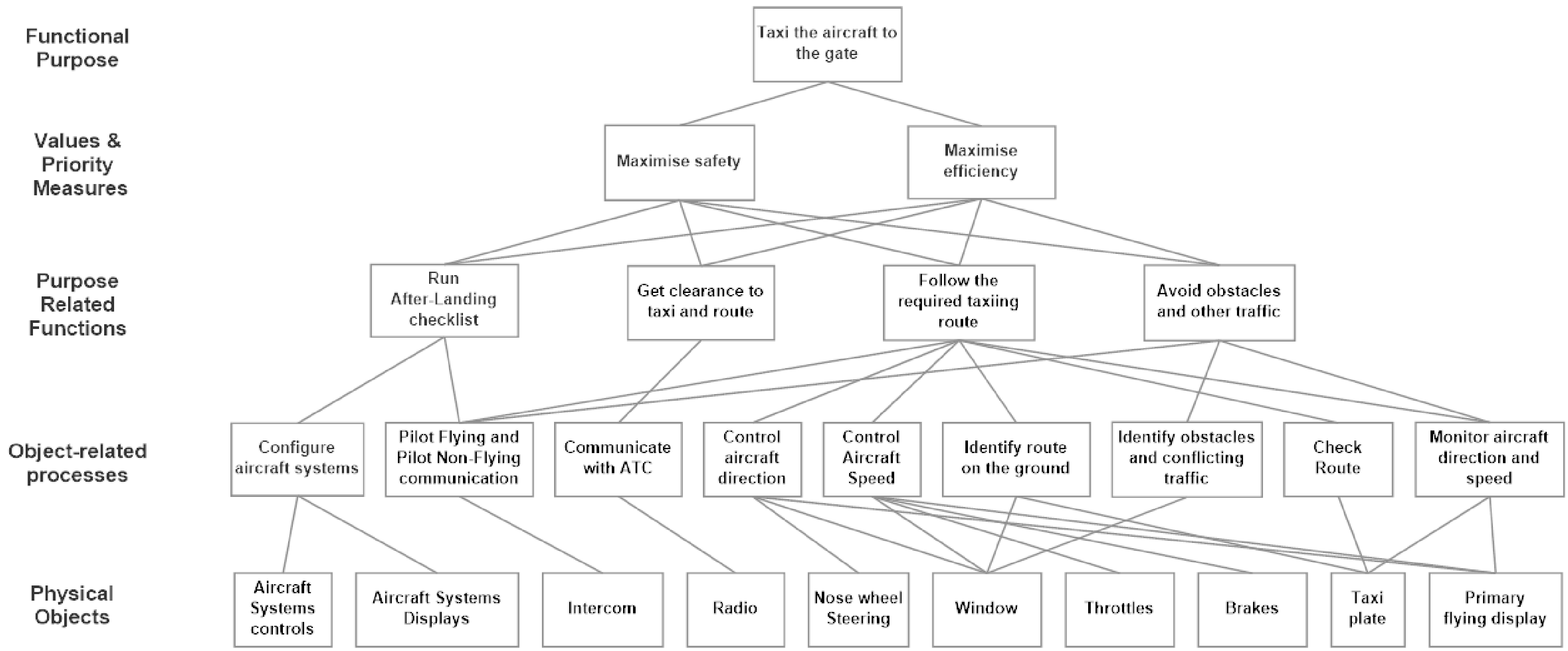


Fig 2 **WDA abstraction hierarchy for taxiing the aircraft to the gate for two-pilot operations (baseline).**

Table 2 Summary of low visibility taxi scenario

<table>
<tr><td colspan="6">Taxi – aircraft is moving on the aerodrome surface under its own power after landing up to parking at the gate</td></tr>
<tr><td colspan="2">Normal Actions
• ATC clearance and routing.
• Routing using airfield plates, taxi markers.
• Low viz procedures.
• Collision avoidance, lookout.
• Crew co-ordination, checks, brakes, speed control etc.
• Park on gate.</td><td colspan="2">Significant Environmental Conditions
• Poor knowledge of the airfield, especially in low visibility. PF requires more attention to lookout/taxi path and speed control PNF required to monitor position/ planned route and co-ordinate with ATC if lost!
• Crossing traffic on the taxiway
• Other traffic on the same taxi way
• Congestion of traffic at the gate (ground vehicles)
• Poor arc of visibility out of the windows on the opposite side of the cockpit to where each pilot is sat (e.g. the pilot in the left-hand seat cannot see the right wing)</td><td colspan="2">Considerations
• Good briefing and CRM essential if in low visibility, so crew takes pre allocated and PF maintains a safe taxi path, looks out (as much as possible) for hazards, keeping speed low. Clear displays or position information required for safe operations in very low visibility.
• Good position SA essential.</td></tr>
<tr><td colspan="3">Description and Significance
• The taxiing task is complicated by the lack of forward visibility and requires co-ordination by the crew by using the printed airport layout to explain outside position cues.
• Difficult to see outside and position/speed cues. PF may not be able to look in to refer to airfield charts, so reliant on PNF for route confirmation and position SA.</td><td colspan="3">Key interactions
• Flight deck and ATC
• Crew co-operation between the pilots. PF taxi and look out. PNF to task for monitoring route/ position may not be able to lookout and support PF.
• Clear displays and warnings to avoid runway incursion. ALSO, A lack of normal cues and position/ hazard avoidance (e.g. narrow taxi way, large wingspan?)</td></tr>
</table>

Analysis of the OESDs, the WDA AH, and the above reveal a number of issues that potentially arise if it is desired to operate the aircraft with just a single pilot:

- *Identifying the taxi route provided by ATC (Figures 1 and 2):* This is critical to the safe conduct of taxiing. If paper taxi plates are in use, identifying the route involves retrieving the taxi plates and identifying the designated route. Agreeing the route usually involves the PNF pointing a finger along the route and the PF checking that it is correct against the clearance received (which the PNF would usually have written down). In the case of electronic flight bags being used, each pilot must bring up the route on the laptop containing the database of airfield plates.
- *Following and monitoring progress along the route*: During the taxiing process, the PF is focussed on lookout and taxiing the aircraft whilst the PNF monitors the process by cross checking the heading and speed of the aircraft against the route shown on the taxi plate.
- *Lookout*: Good lookout is essential to ensure that the aircraft does not collide with obstacles or other aircraft (Figures 1 and 2): ATC should procedurally de-conflict taxiing aircraft but in reduced visibility an aircraft may be on the wrong taxiway after taking a wrong turning. In the absence of the PNF, the PF cannot determine if there are any aircraft approaching from the right-hand side once he starts to turn, and cannot see if the right wingtip is clear of obstacles (given that on many modern airliners, the pilots are unable to see the wingtips from the cockpit). Taxiing an aircraft in reduced visibility requires careful lookout to pick up the cues indicating the correct path (e.g. the taxiway centreline markers, indications of junctions marked on the taxiways and marker boards at the side of the taxiway) while proceeding at a speed compatible with the range of visibility. The field of view or vision from the pilots' seat is also highly compromised when looking across the flight deck and to the front of the aircraft. The pilots are also sitting forward of the front wheel (to illustrate, by 5m on an Airbus A320 and 3.7m on a Boeing 757-200 and are also 22m ahead of the main wheels). This means that the crew must travel past the point at which the turn should start and they travel on a different path to the front wheel and then the main wheels, moving sideways at the start of the turn. During the taxiing process, the PF is focussed on lookout and taxiing the aircraft whilst the PNF monitors the process by cross checking the heading and speed of the aircraft against the route shown on the taxi plate.
- *Carrying out the 'After Landing' checklist (Figures 1 and 2)*: This activity is undertaken in parallel with taxiing for several reasons. Fuel Economy: Some two-engine aircraft can taxi using only one engine, so the other engine is shut down for to save fuel. However, this means that engine's generator does not produce any power, limiting the number of aircraft systems that can be operated, hence the Auxiliary Power Unit must be started. Expediency: Completing the 'After Landing' checklist before the aircraft reaches the gate reduces the time required to turn the aircraft around at the gate. Safety: Equipment such as the weather radar is switched off to prevent ground handling staff from being exposed to radar emissions. In two pilot operations, the conduct of the After Landing Checklist rests with the PNF as the PF is focussed on the taxing task, controlling throttles, steering and brakes whilst looking out. In single pilot operations, the pilot cannot simultaneously action the checklist whilst taxiing.
- *Communications between PF and GP*: In two pilot operations (Figures 1 and 2) the PF and PNF communicate over the intercom. They can speak directly to each other, but the headset for the intercom is also used for the radios. The intercom uses a 'hot-mike' system which means that transmission over the intercom is triggered by the detection of speech, rather than requiring the operator to press a transmit button. The transmit button must be pressed to transmit over the radio. In single pilot operations, the PNF and GP cannot communicate over

the intercom, as it is purely internal to the aircraft. Therefore, they will need an alternative means of communication.

Proposed Solutions

The new functionalities required in the single pilot aircraft can be identified from the analysis of the tasks that fall within the 'swim lane' allocated to the PNF in Figure 1. From this, the following outline solutions to the issues raised in the preceding section were proposed:

- *Identifying correct taxi route*: A Global Positioning System (GPS) application presented on the aircraft displays and replicated on the Ground Station, would enable the pilot to check progress along the route and the GP to monitor both the correct entry of the route and correct progress along it. A significant enhancement would be taxi commands presented on a Head Up Display (HUD) to provide route and turning point indications. This would require a control facility to bring up the appropriate taxiing displays and to enter the prescribed route. This type of system could be enhanced even further by providing the capability for ATC to transmit the route directly to the GPS system via data link (see Figure 3).
- *Lookout*: The use of enhanced vision systems (such as Infra-red to improve pilot vision at night or in reduced visibility) in combination with the large screen Head-Down Display and a Head Up Display could be exploited to provide the PF with a wide-angle view of the outside world showing obstacles and other aircraft which would not otherwise be visible. A proximity warning system (akin to parking sensors on a car) could be used to sense nearby obstacles and give an audio warning to the PF.
- *After Landing Checklist completion:* There are several potential solutions to this problem. The 'After Landing' checklist could be completed in its entirety before taxiing commences. However, this would require the aircraft to be stationary during the process, leading to the requirement for a holding area near the runway for all aircraft completing after landing checks. An alternative would be to action only essential checks before taxiing, completing the remainder of the actions at the gate. Using this approach only the actions that must be completed to facilitate taxiing and the safe arrival at the gate (such as APU – Auxiliary Power Unit - start, engine shutdown and switching of the weather radar) are conducted before taxiing commences, with the rest of the actions completed at the gate. This minimises the time that the aircraft must be stationary on the taxiway after turning off the runway. Replicated system status displays on the GP's station would allow them to monitor the pilot's actions.
- *Communications between PF and GP*: the simplest solution is for the PF and GP to communicate over the radio, although the implementation of a hot-mike system specific to that channel would have to be investigated. A hot-mike system for the GP would have to be selective as they may be in communication with more than one aircraft.

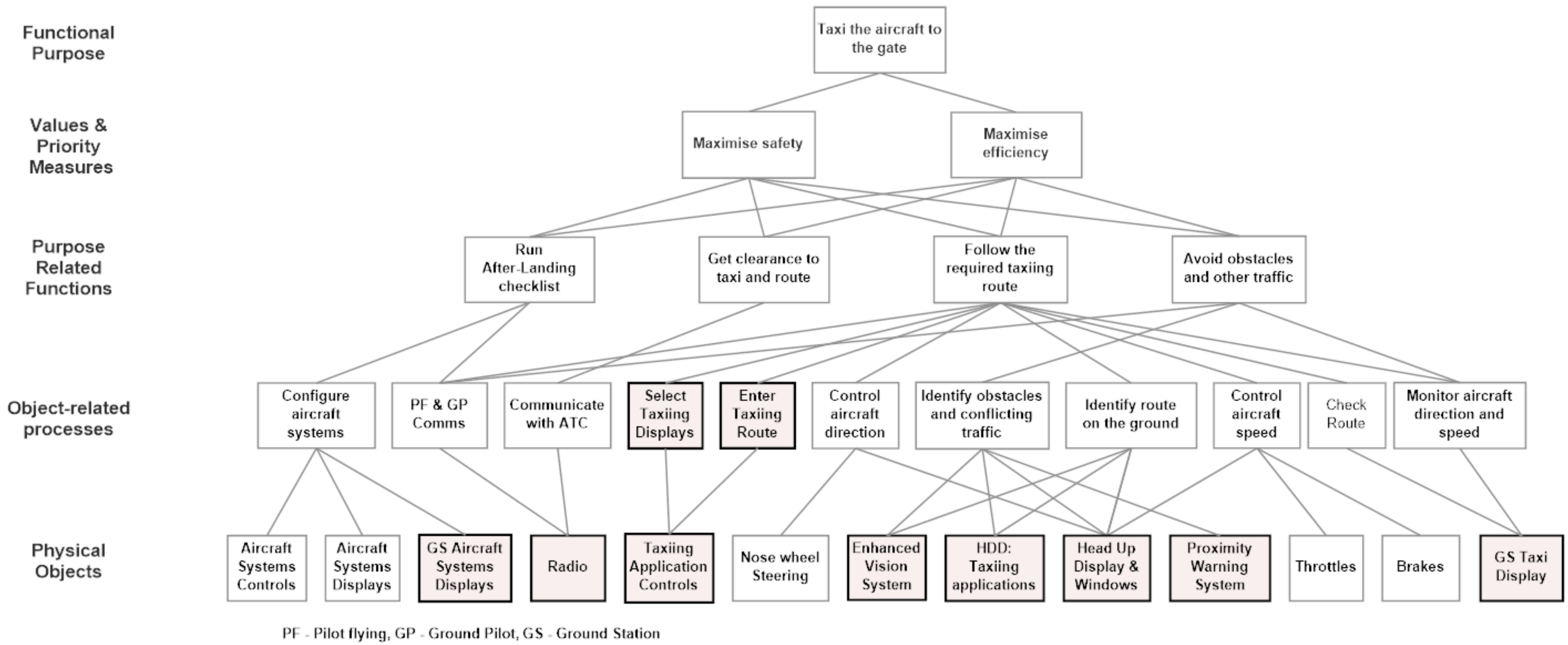


Fig 3 **WDA abstraction hierarchy for taxiing the aircraft to the gate for single pilot operations incorporating new technologies and GP-based functions.**

Fig 4a **OESD for taxiing the aircraft to the gate for single pilot operations incorporating new technologies and GP-based functions.**

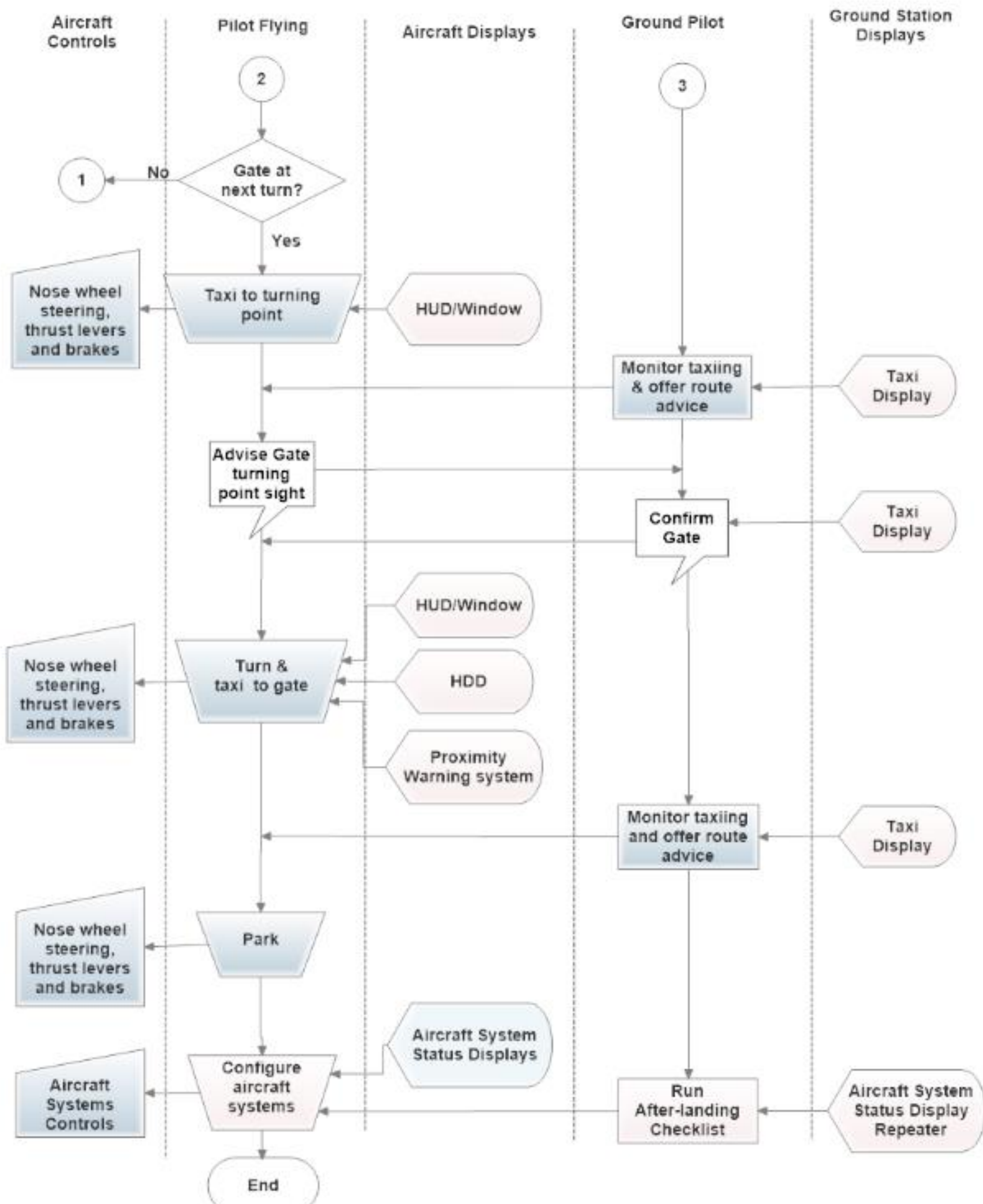


Fig 4b **OESD for taxiing the aircraft to the gate for single pilot operations incorporating new technologies and GP-based functions (continued).**

The potential utility of these solutions can be evaluated by incorporating them into a revised AH and OESD (Figures 3 and 4 respectively). The proposed system components are shown as new physical objects (darker shaded boxes) in Figures 3 and 4. To re-iterate, the design upon which this solution is predicated envisions that the pilot in the aircraft will be aided by a GP and by the selective implementation of extant technologies (e.g. high integrity datalink; helmet mounted displays) developed from single crew military aircraft and UASs. Comparison of the elements in Figures 1 and 2 with Figures 3 and 4 illustrate how the tasks and functions undertaken by the PNF have now been subsumed and/or replaced by incorporating new technology or by the GP function.

With new physical objects in the system, it would be expected to see new object related processes in the AH. In this case, only two were found to be necessary (Figure 3) – 'select taxiing displays' and 'enter taxiing route' (also shown as shared objects). These new processes are also reflected in the OESD. However, if the baseline and revised AHs (Figures 2 and 3) are compared, it can be seen that the upper levels of the AH remain unchanged. This reflects that the overall purpose of the system (taxiing the aircraft to the gate) and the priorities which constrain how this task should be achieved (maintaining safety and efficiency) must be achieved even if the system for delivering these requirements is modified. In this case, the high-level, purpose related functions also remained unchanged. The revised OESD captures the revised action sequences and interactions with the new system components.

DISCUSSION

The analysis of the taxi in after landing scenario using a combination of OESDs and AHs from WDA identifies both the new technologies required to support a single crew aircraft and provides information concerning the allocation of task between pilot and ground station operator. Although, the taxi phase may not be considered a critical stage of flight, it does illustrate the stress and effects of a simple task; follow a taxi route, which is affected by poor visibility, on a busy airport with a complicated taxi way system and thus emphases the reliance on a second crew member.

The analyses in Figure 2 suggest that the majority of the functions that the PNF undertakes in the baseline, two-crew analyses are associated with checking, surveillance and monitoring activities. These must be undertaken by either the PF, GS (Ground Station) and/or automated aircraft systems in the case of single pilot operations. Many of these checking and monitoring tasks previously undertaken by the PNF can be allocated either to automated systems (such as the taxi-route sat-nav system) or the monitoring personnel in the GS (see Figure 3). The single pilot is now responsible for all surveillance tasks, but is now aided by an enhanced HUD taxi display, providing guidance cues along with a surveillance facility to detect other aircraft in the proximity. Any outputs from the aircraft automation would be best provided to the pilot via the auditory channel enabling them to remain 'head up and eyeballs out' during the landing and subsequent taxi-in to the gate. This approach to the analysis and re-allocation of required functions is similar to the approach described in Harris, Stanton & Starr (2015). However, in this case by using a combination of OESDs and WDAs, the functional description of the new equipment and revised workflows can be specified in much more detail. By doing this, it is possible to define in greater detail the specific flight deck equipment (and its outline method of operation) required for development of a single crew commercial aircraft than in the earlier papers using this approach.

The utilisation of OESDs and WDAs for the functional description of new equipment and procedures that may be required for the operation of a single crew aircraft allows the representation of context and other aspects of the wider socio-technical system (Fuld 2000; Challenger, Clegg, & Shepherd 2013). Both techniques are technology/human agnostic and different potential configurations incorporating on- and off- aircraft actors can be incorporated to perform an initial assessment of alternative potential design solutions. The use of multiple, complementary Human Factors methods again provides a richer analytical picture (Stanton et al, 2009; Carayon et al. 2015). This is particularly important in aeronautics as a result of the many environmental and regulatory constraints on the system.

The major shortcoming of the OESD approach is that it cannot describe the cognitive load imposed on the operator (pilot) at a given point in time, only the tasks being undertaken (by either the human or machine). The technique needs developing to encompass an indication of likely pilot workload which would help to define options for the dynamic functional allocation of tasks, particularly at times of high cognitive demand. This is also true of the AH in the WDA analysis.

The use of OESDs and WDA analyses at the design stages of subsequent iterations of the single-crew flight deck concept described in this paper would be beneficial for defining the appropriate dynamic re-allocation of tasks to intelligent on-board automation (knowledge-based assistance) when it has been detected that pilot workload is increasing beyond pre-set limits. This approach to the dynamic allocation of assistance is being developed for the support of UAV operators (see Schulte & Meitinger, 2010; Schulte & Meitinger, 2012).

RECOMMENDATIONS FOR FUTURE WORK

If tasks and functions are to be distributed between the flight deck and a ground station component, then crewing advantages can only be obtained if fewer people are engaged on supporting the PF from the ground than would be employed as a PNF in a conventional two-crew aircraft. However, further work is required to establish what ratio of ground stations to aircraft will be necessary to maintain safe and efficient operations in all conditions and circumstances. Walter Johnson, quoted in Aviation Week and Space Technology (12 January 2015) suggested that a single ‘Super Dispatcher’ at a ground station could service 12 aircraft, however this figure was based upon earlier conceptual analyses rather than empirical data (see Bilimoria, Johnson & Schutte, 2014).

Ensuring the safety of a single pilot system where operations are potentially distributed across a ground and air component will pose a significant challenge for the airworthiness regulators. Current certification processes apply to only the aircraft, however the proposed architecture shares features with Remotely Piloted Air Systems (RPASs). These commonly use a safety-case based approach as the system is distributed between a ground and air component (e.g. CAP 772: Unmanned Aircraft System Operations in UK Airspace – Civil Aviation Authority, 2015: UK Ministry of Defence DEF STAN 00-970 Part 9, 2002). STAMP-STPA (Systems Theoretic Accident Model and Process - System-Theoretic Process Analysis) is one such method that may be able to satisfy such an approach. STPA is a predictive risk assessment method within the STAMP framework (Leveson, 2004; 2011). This approach has already been used for the retrospective study of aviation accidents (e.g. Allison, *et al*., under review) but has the potential to be used in a safety assurance role for a distributed, complex system, such as the one proposed.

Thomas Edwards, Director of Aeronautics at NASA Ames Research Center, has suggested that the issue is not so much one of should single pilot operations be adopted, but ‘*is one pilot a logical stepping stone on the way to zero pilots?*’ (Comerford, et al., 2013, p. 9). The single crew aircraft may only be the next step of doing more with fewer people on the flight deck.

REFERENCES

ACROSS project http://www.across-fp7.eu/

ALLISON, C.K., REVELL, K.M., SEARS, R. STANTON, N.A. (Under Review). Systems Theoretic Accident Model and Process (STAMP) Safety Modelling Applied to an Aircraft Rapid Decompression Event. *Safety Science.*

AVIATION WEEK & SPACE TECHNOLOGY, 2015, NASA Advances Single-Pilot Operations Concepts: 'Super dispatcher' fills in for a dozen first officers in NASA studies. *Aviation Week & Space Technology, Jan 12, 2015*. Retrieved from http://aviationweek.com/technology/nasa-advances-single-pilot-operations-concepts (16 November, 2016).

BILIMORIA, K.D., JOHNSON, W.W & SCHUTTE, P.C. 2014, Conceptual Framework for Single Pilot Operations. (2014). *Proceedings of International Conference on Human-Computer Interaction in Aerospace (HCI-Aero 2014)*, July 30 – August 1, 2014. Santa Clara, California, USA.

BOEING AIRCRAFT COMPANY, 2006. *Boeing 757 Flight Crew Training Manual,* October 31, 2006. (Author: Seattle WA).

BONNER, M., TAYLOR, R., FLETCHER, K. & MILLER, C. 2000, Adaptive Automation and Decision Aiding in the Military Fast Jet Domain, in, D.B. Kaber & M.R. Endsley (Eds.). *Human Performance, Situation Awareness and Automation: User-Centred Design for the New Millenium.* (Omnipress, Madison, WI), 154- 159.

CARAYON, P., KIANFAR, S., LI, Y., XIE, A., ALYOUSEF, B., & WOOLDRIDGE, A. 2015, A systematic review of mixed methods research on human factors and ergonomics in health care. *Applied Ergonomics, 51, 291-321.*

CARSTEN, O., LAI, F.C.H., BARNARD, Y., JAMSON, A.H. & MERAT, N., 2012, Control Task Substitution in semi-automated Driving: Does It Matter What Aspects Are Automated? *Human Factors, 54, 747-761.*

CHALLENGER, R., CLEGG, C.W., & SHEPHERD, C. 2013, Function allocation in complex systems: reframing an old problem. *Ergonomics,* **56,** 1051–1069.

CIVIL AVIATION AUTHORITY, 2015, *Unmanned Aircraft System Operations in UK Airspace – Guidance (6th Edition). CAP 722.* London: Civil Aviation Authority.

CIVIL AVIATION AUTHORITY, 2013, *Monitoring Matters, Guidance on the Development of Pilot Monitoring Skills. CAA Paper 2013/02.* London: Civil Aviation Authority.

COMERFORD, D., BRANDT, S.L., LACHTER, J., WU, S-C., MOGFORD, R., BATTISTE, V. & JOHNSON, W.L. (2013), *NASA's Single Pilot Operations Technical Interchange Meeting: Proceedings and Findings (NASA/CP-2013-216513).* (Moffett Field, CA: National Aeronautics and Space Administration, Ames Research Center).

CORBRIDGE, C., & COOK, C. A. 1997, The Role of Function Allocation in the Design of Future Naval Systems, in, E. Fallon, L. Bannon, & J. McCarthy (Eds.) *ALLFN'97 Revisiting the Allocation of Function Issue: Proceedings of the 1st International Conference on Allocation of Functions, Volume 1* (IEA Press, Louisville, KY), 73-88.

CROFT, J. 2015, NASA Advances Single-Pilot Operations Concepts. *Aviation Week & Space Technology, January 15 - February 1.*

DEARDEN, A., HARRISON, M. & WRIGHT, P. 2000, Allocation of Function: Scenarios, Context and the Economics of Effort. *International Journal of Human Computer Studies* **52***,* 289–318.

DEUTCH, S. & PEW, R.W. 2005*, Single Pilot Commercial Aircraft Operation (BBN Report No. 8436).* Cambridge, MA: BBN Technologies.

EASA 2011 European Action Plan for the Prevention of Runway Incursions Edition 2.0 (EASA, Cologne)

EASYJET PLC 2013. *Annual report and accounts 2013,* Available from http://corporate.easyjet.com/~/media/Files/E/Easyjet-Plc-V2/pdf/investors/result-center-investor/annual-report-2013.pdf (accessed 17 November 2016).

FULD, R.B. 2000, The Fiction of Function Allocation, Revisited. *International Journal of Human Computer Studies* **52***,* 217–233.

HARRIS, D. 2007, A Human-Centred Design Agenda for the Development of a Single Crew Operated Commercial Aircraft. *Aircraft Engineering and Aerospace Technology,* **79**, 518-526.

HARRIS, D., STANTON, N.A. & STARR, A. (2015). Spot the Difference: Operational Event Sequence Diagrams as a Formal Method for Work Allocation in the Development of Single Pilot Operations for Commercial Aircraft. *Ergonomics, 58, (11),* 1773–1791.

HUDDLESTONE, J. 2015 *Future Flight Deck Concept of Operation and Operational Scenarios* (Deliverable D1.2), Future Flight Deck, Aerospace Growth Partnership.

JENKINS D.P., STANTON N.A., WALKER G.H. & SALMON P.M., 2009, *Cognitive Work Analysis: Coping with Complexity*, (Ashgate, Aldershot).

KEINRATH, C., VAŠEK, J. & DORNEICH, M. 2010, A cognitive adaptive man-machine Interface for future Flight Decks, in, A. Droog & M. Heese (Eds) *Performance, Safety and Well-being in Aviation Proceedings of the 29th Conference of the European Association for Aviation Psychology* (20-24 September 2010, Budapest, Hungary). European Association of Aviation Psychology.

KIRWAN, B., & AINSWORTH, L.K. 1992, *A Guide to Task Analysis*, (Taylor and Francis, London).

KURKE, M.I. (1961). Operation Sequence Diagrams in System Design. *Human Factors,* ***3****,* 66-73

LACHTER, J., BRANDT, S.L. & BATTISTE, V., 2014, Toward Single Pilot Operations: Developing a Ground Station. *Proceedings of International Conference on Human-Computer Interaction in Aerospace (HCI-Aero 2014)*, July 30 – August 1, 2014. Santa Clara, California, USA.

LEVESON, N., 2004, A new accident model for engineering safer systems. *Safety Science*, **42**, 237-270.

LEVESON, N., 2011, *Engineering a Safer World: Systems Thinking Applied to Safety,* (MIT Press Cambridge, MA).

MCILROY, R. C. & STANTON, N. A., 2011, Getting past first base: Going all the way with Cognitive Work Analysis, *Applied Ergonomics*, **42**, 358-370.

NAIKAR, N. (2006). Beyond Interface Design: Further Applications of Cognitive Work Analysis. International Journal of Industrial Ergonomics, 36, 423–438.

NORMAN, R.M., 2013, Economic Opportunities and Technical Challenges for Reduced Crew Operations. In, D. COMERFORD, S.L. BRANDT, J. LACHTER, S-C. WU, R. MOGFORD, V. BATTISTE & W.L. JOHNSON, 2013), *NASA's Single Pilot Operations Technical Interchange Meeting: Proceedings and Findings (NASA/CP-2013-216513),* (Moffett Field, CA: National Aeronautics and Space Administration, Ames Research Center) 31-35.

ONKEN, R. 1994, *Human-Centred Cockpit Design Through the Knowledge-Based Cockpit Assistant System CASSY*. NATO DRG Panel 8 Workshop on Improving Function Allocation for Integrated System Design. (TNO Institute for Perception, Soesterberg, NL).

ONKEN, R., 1997, *Functional Development and Field Test of CASSY – A Knowledge Based Cockpit Assistant System*, Knowledge-Based Functions in Aerospace Systems, AGARD Lecture Series 200, (AGARD, Neuilly-sur-Seine, France).

RASMUSSEN, J., PEJTERSEN, A. & GOODSTEIN, L.P. (1994). *Cognitive Systems Engineering,* (Wiley, New York).

RYANAIR (2009). Full Year Results, 2009. Available from: http://www.ryanair.com/doc/investor/2009/q4_2009_doc.pdf (accessed 17 November, 2017).

SANDERS, M.S. & McCORMICK, E.J. 1993, *Human Factors in Engineering and Design*, (McGraw-Hill Publications, New York, NY).

SCHULTE, A. & STÜTZ, P. 2001, Cognitive concepts in mission management for air-to-ground attack aircraft, in D. Harris (Ed.), *Engineering Psychology and Cognitive Ergonomics, Volume 5*, (Aldershot, Ashgate), 23-30.

SCHULTE, A., & MEITINGER, C. (2009). Cognitive and Cooperative Automation for Manned-unmanned Teaming Missions. In, *Advanced Automation Issues for Supervisory Control in Manned-unmanned Teaming Missions.* NATO Research and Technology Organization, EN-SCI-208. (NATO/OTAN: Neuilly-sur-Seine).

SCHULTE, A., & MEITINGER, C. (2010). Measuring self-adaptive UAV operators' load-shedding strategies under high workload. In D. Harris (Ed) *Engineering Psychology and Cognitive Ergonomics*, Springer: Berlin Heidelberg, (342-351).

SCHULTE, A., & MEITINGER, C. (2012). Introducing Cognitive and Co-operative Automation into UAV Guidance Work Systems. In, F. Jentsch & M.M. Barnes (Eds.). *Human-robot interactions in future military operations*, (Aldershot: Ashgate), 145-170.

STANTON, N.A., HARRIS, D. & STARR, A. 2014, Modelling and Analysis of Single Pilot Operations in Commercial Aviation, in, *Proceedings of HCI Aero 2014, 30 July – 1 August, 2014*, Santa Clara, CA, USA.

STANTON, N.A., HARRIS, D., & STARR, A., 2016, The Future Flight Deck: Modelling dual, single and distributed crewing options. *Applied Ergonomics, 53,* 331-342.

STANTON, N.A., SALMON, P., HARRIS, D., MARSHALL, A., DEMAGALSKI, J.M., YOUNG, M.S., WALDMANN, T. & DEKKER, S.W.A., 2009, Predicting pilot error: Testing a new methodology and a multi-methods and analysts approach. *Applied Ergonomics 40(3),* 464-471.

STANTON, N.A., SALMON, P.M., RAFFERTY, L.A., WALKER, G.H., BABER, C. & JENKINS, D.P. 2013, *Human Factors Methods: A Practical Guide for Engineering and Design (2nd Edition)*, (Aldershot, Ashgate).

STANTON, N.A., SORENSEN, L.J. & BANKS, A.P. 2011, Back to SA school: contrasting three approaches to situation awareness in the cockpit. *Theoretical Issues in Ergonomics Science,* **12**, 451-471.

STÜTZ, P. & SCHULTE, A. 2001, Evaluation of the Cockpit Assistant Military Aircraft (CAMA) in flight trials, in D. Harris (Ed.), *Engineering Psychology and Cognitive Ergonomics, Volume 5* (Aldershot, Ashgate), 15-22.

TAYLOR, R.M., HOWELLS, H. & WATSON, D. 2000, The Cognitive Cockpit: Operational Requirement and Technical Challenge, in, P.T. McCabe, M.A. Hanson & S.A. Robertson (Eds.) *Contemporary Ergonomics 2000*. (Taylor and Francis, London), 55-59.

VICENTE, K. J., 1999, Cognitive Work Analysis: Toward Safe, Productive, and Healthy Computer-Based Work, (Lawrence Erlbaum Associates, Mahwah, NJ).

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