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The Future Flight Deck: Modelling dual, single and distributed crewing options

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ABSTRACT

It is argued that the barrier to single pilot operation is not the technology, but the failure to consider the whole socio-technical system. To better understand the socio-technical system we model alternative single pilot operations using Cognitive Work Analysis (CWA) and analyse those models using Social Network Analysis (SNA). Four potential models of single pilot operations were compared to existing two pilot operations. Using SOCA-CAT from CWA, we were able to identify the potential functional loading and interactions between networks of agents. The interactions formed the basis on the SNA. These analyses potentially form the basis for distributed system architecture for the operation of a future aircraft. The findings from the models suggest that distributed crewing option could be at least as resilient, in network architecture terms, as the current dual crewing operations.

KEYWORDS: Flight Deck, Crewing, Modelling, Cognitive Work Analysis, Social Network Analysis

HIGHLIGHTS:

- Contrasting different crewing options with CWA and SNA
- Identification of functional loadings on agents
- Using data from SOCA-CAT as input into SNA
- Analysis of networked in interactions between agents
- Using network analysis to identify system resilience

INTRODUCTION

The trend in flight deck design over the past half century has been one of progressive 'de-crewing'. Fifty years ago, it was not uncommon for there to be five crew on the flight deck of a civil airliner (two Pilots; Flight Engineer; Navigator and Radio Operator). Today, just two pilots, accomplish the same tasks once undertaken by five. Many functions are now wholly or partially automated. Consequently the role of the pilot has changed from one of being a 'flyer' to one of being a systems/flight deck manager.

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). Crew costs for smaller commercial aircraft can be between 15% and 35% of the aircraft direct operating costs (Alcock, 2004). Annual accounts from a typical low-cost operator suggest that even for a larger airliner, the crew represent nearly 19% of operating costs (excluding fuel and propulsion – easyJet, 2013). The scope to make significant cost savings with the current common configuration for aircraft (cylindrical fuselage with wings, rudder and tail plane) is now limited. This configuration is approaching the end of its development potential. Alternative configurations such as the blended wing body concept which offer considerable structural and aerodynamic advantages, have met with limited enthusiasm from potential passengers. Problems of ensuring a safe and efficient means of passenger evacuation have also been identified (Galea, Filippidis, Wang, Lawrence & Ewer, 2011). This configuration also needs a great deal of development in other areas (such as flight control systems and structural testing) before it will be suitable for service entry. Reducing the number of crew on the flight deck to just a single pilot will produced significant cost savings, especially in smaller commercial aircraft operated on shorter and 'thinner' (lower demand) routes.

Some manufacturers (e.g. Embraer) are already developing the technology for a single crew aircraft, as are avionics suppliers (e.g. Honeywell – see Keinrath, Vašek and Dorneich, 2010). The approaches being adopted in these instances centre upon the development of sophisticated airborne technology to assist the pilot (e.g., Intelligent Knowledge-Based Systems and adaptive automation). This approach is also adopted in other research programmes looking at flight deck automation and crewing, for example the development of an Electronic Standby Pilot (ESP) as part of the Advanced Cockpit for the Reduction of Stress and Workload (ACROSS) project (see http://www.across-fp7.eu/). The medium term objectives of the ACROSS project are concerned with reducing the number of flight deck crew in the cruise phase in long-haul flights to permit crew to rest and help prevent fatigue. It is anticipated that the same technology will aid in the case of partial (or even full) flight crew incapacitation. The longer term objectives of the project are to form the basis for potential single crew operations.

A similar approach has been adopted by other researchers in the past, particularly in the military domain, but with only mixed success (e.g. the COGnitive cockPIT – COGPIT programme - Bonner, Taylor, Fletcher and Miller, 2000; Taylor, Howells and Watson, 2000; and the Cockpit Assistant Military Aircraft – CAMA programme - Schulte and Stütz, 2001; Stütz and Schulte, 2001). CASSY (the Cockpit ASsistant System) was a civil aircraft version of the latter developed by the same team (see Onken, 1994; Onken, 1997). The Cognitive Adaptive Man-Machine Interface (CAMMI) project (Keinrath, Vašek and Dorneich, 2010) also makes use of extensive AI software in its approach to adaptive automation. A later requirements analysis for developing concepts for single pilot operations was also predicated upon the notion of incorporating extensive pilot automated assistance on the flight deck, particularly synthetic vision systems; data linking and direct voice input/output systems (Deutch and Pew, 2005). The main arguments for the use of two members of flight deck crew centre around issues concerned with pilot workload (specifically instances of workload peaks); the reduction of flight crew error and pilot incapacitation. However, many of the assumptions are either questionable or are becoming outdated. Don, can you expand on this point please?

From the perspective of the person in command of any aircraft, there is a workload 'cost' associated with the management of crew on the flight deck. The requirement to coordinate crew, cooperate and communicate on the flight deck itself has workload associated with it. Doubling the number of crew does not half the workload. Furthermore, modern flight decks are already certificated so that they can be operated by a single-member of flight deck crew (see FAR/CS 25.1523). Automated flight deck systems have already considerably reduced pilot workload (Weiner & Curry, 1980; Harris, 2003).

While the second crew member may distribute the workload around the flight deck somewhat, it can be also be argued that they actually introduce an error mode. Poor CRM (Crew Resource Management) has been implicated as a contributory factor in nearly 23% of all fatal commercial jet aircraft accidents (CAA, 2008). The effectiveness of the second pilot as an 'error checker' is also questionable. Omission of action or inappropriate action was implicated in 39% of accidents and an incorrect application of procedures or a deliberate non-adherence to procedures was implicated in a further 13% (Civil Aviation Authority, 2008). Becoming 'low and slow' (a failure to cross monitor the flying pilot) was a factor in 12% of accidents. As a cross check on the position of the aircraft the PM's effectiveness would also seem to be questionable as a lack of positional awareness was identified as a causal factor in 27% of cases (Civil Aviation Authority, 2008). This is quite a crude analysis however. It is acknowledged that what these data do not show is in how many cases the second pilot trapped an error made by the other pilot and avoided an accident: this is unknown and unknowable. However, observational data obtained from routine flights reported that 47.2% of errors committed by Captains involved intentional non-compliance with Standard Operating Procedures (SOPs) or regulations: 38.5% were unintentional procedural non-compliance (Thomas, 2003). Thomas also reports that in observations of line operations crews did not demonstrate effective error detection, with more than half of all errors remaining undetected by one or both of the flight crew. As a result it can be argued that removing one of the pilots actually reduces the scope for accidents occurring as a result of miscommunication or mis-understanding between the pilots and that removing the PM does not double the workload on the flight deck.

Perhaps the greatest concern for the development of a single-crew aircraft is that associated with pilot death, incapacitation or impairment. However, such instances are very rare. A study of in-flight medical incapacitations in US airline pilots between 1993 and 1998, found only 39 instances of incapacitation and 11 instances of impairment (DeJohn, Wolbrink and Larcher, 2004). The rate of in-flight medical events (encompassing both types) was 0.058 per 100,000 flight hours. The probability that one of these events would *subsequently* result in an accident was calculated to be 0.04. DeJohn, Wolbrink and Larcher (2004) observed that the safety of the flight was seriously impacted in only seven cases and resulted in two non-fatal accidents. A later study of UK commercial pilots by Evans and Radcliffe (2012) suggest that the annual in-flight incapacitation rate was 0.25%, however this study is seriously flawed in than it was not weighted by flight hour and the rate is expressed as a percentage of all UK registered pilots (irrespective of flight hours accumulated by each, per year).

It is argued that with the judicious use of existing equipment, there are no major reasons why a single pilot operated commercial aircraft is not feasible in the very near future using existing technology. Military aviation has flown complex, high performance single crew aircraft for many years and Unmanned Air Vehicles (UAVs) are now commonplace. UAV technology has matured and such aircraft are now regularly being used for national border and port security, homeland surveillance, scientific data collection and telecommunications services (REF). Airworthiness standards for their design and operation in civil airspace are being developed on both sides of the Atlantic (e.g. UK Civil Aviation Authority, 2010 - *Unmanned Aircraft System Operations in UK Airspace – Guidance (CAP 722)).* Several UAVs are now the size of a small aircraft, with performance similar (or exceeding) that of a conventional aeroplane. One fundamental difference between UAVs and commercial aircraft is that pilots of commercial aircraft have a duty of care to the passengers that they are carrying (REF). Whether the same sense of responsibility can be translated to remote pilots remains to be seen, but is beyond the scope of this paper.

The greatest obstacle to the operation of civilian, single pilot, aircraft is not the technology *per se*. Rather, the barriers are: combining the ground and airborne technologies, designing the user interfaces and developing new concepts of operations to make such an aeroplane safe and useable in a wide range of normal and non-normal operating situations (when flown by a typical commercial pilot). That is to say that the Human Factors requirements are the prime driver in this case, not the technology. The concept evaluated in this paper is based upon an alternative design approach to that of utilising a large amount of on-board, complex, computing (e.g. that using agent-based software) first described by Harris (2007). The concept, uses a socio-technical systems-based design philosophy utilising a great deal of currently existing technology. In this case the control and crewing of the aircraft is distributed in real time across both the aircraft's flight deck and ground stations (see also: Stanton, Harris and Starr, 2014). The second pilot is not *replaced* by on-board Artificial Intelligence or Intelligent Knowledge-Based Systems, which would be both difficult to develop and challenging to certificate; they are merely *displaced*.

DESIGN APPROACH

The proposed approach 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. The initial high-level design architecture proposed for operating the Single Crew Aircraft consists of several discrete elements (Stanton, Harris and Starr, 2014):

- The aircraft itself (including pilot)
- Ground-based component including:
    - 'Second pilot' support station/office
    - Real-time engineering support
    - Navigation/flight planning support
- System 'Mirror'.

This is the initial envisaged instantiation of the system upon which to base a cognitive work analyses in order to evaluate its efficacy and to identify required technology development paths. The design of this single crew aircraft operations system is intended to form the basis of incremental developments, incorporating subsequent airborne pilot-support technology as it is developed. This will allow the further rapid development of the concept.

Aircraft component

In many ways the aircraft component will be little different to current types. The requirements are that aircraft should be able to function in all types of airspace without any special Air Traffic Control/Air Traffic Management (ATC/ATM) procedures and should be able to be flown by regular Airline Transport Pilots Licence (ATPL) qualified professional pilots without extraordinary training. It should exhibit an equivalent level of safety to fourth-generation modern airliners. Initially such an aircraft will be optimised for shorter-range, low cost operations (including cargo operations) and for 'thinner' routes where cost of operation is a critical factor. Emphasis will be placed upon reduction of workload and error by simplification of operation.

Ground-based component

The ground-based component's primary functions are to support the pilot (e.g. in navigation, system management, air traffic control/management support or fault diagnosis) not necessarily to duplicate their skills and functions. Suitably skilled personnel on the ground may simultaneously support several aircraft (resulting in economy of scale and reduction in duplication of effort). Furthermore, these personnel need not necessarily have the same skill set as a pilot rather they could be specialists in navigation, communications or avionics systems. In the case of the single crew aircraft, *control* from a ground station would only be required in the advent of pilot incapacitation, although *assistance* from the ground may be required in other circumstances, such as high workload (e.g. take-off/landing) or abnormal (e.g., re-routing/bad weather/emergency) situations. This approach would allow ground-based operators to undertake many of the key roles of the second pilot but do so for several aircraft simultaneously. This emphasises that the design of a single crew aircraft is not simply concerned with the re-design of the flight deck. It requires a change in the overall operating philosophy.

'Second Pilot' Support Station/Office The primary functions of the ground-based 'second-pilot' station/office is to provide real-time support for the pilot on the aircraft, as required and to assist in flight planning and pre-flight preparation. If the hierarchy of tasks when flying an aircraft can be conceptualised as 'Aviate'; 'Navigate'; 'Communicate' and 'Manage', whenever possible the 'Aviate' component will remain on the flight deck itself. However, if necessary it will be possible to operate the aircraft remotely from this position. It is envisaged that this support station will be able to support a number of aircraft.

The function of this aspect of the ground-support element is four-fold:

- Prior to flight, the ground-based support function provides a cross check of flight planning data.
- When pilot workload is high, if required the operator in the ground-based workstation may assume many of the duties of the second pilot normally on-board the aircraft.
- During non-normal, abnormal or emergency situations the operator in the ground-based workstation will also assume the duties normally undertaken by the second pilot, however this will also be in conjunction with other support (provided as required) by engineering support and navigation/flight planning support elements.
- In the event of pilot incapacitation the aircraft can be 'flown' from the ground station (in the same manner as a UAV). It is envisaged that any direct operation from this position will be undertaken via the aircraft's automation; direct operation via the primary flight controls will be a last resort.

The main focus of ground-based support from this operator station will be on aircraft configuration management, and short-term navigation and communication support to the pilot. Emphasis will be placed upon decision aiding aspects of pilot support.

This station will be crewed by pilots qualified on the single crew aircraft, who 'rotate' through the post in between actually flying the aircraft. This should enhance the shared Situation Awareness between ground and air components.

Real Time Engineering Support The single crew aircraft will routinely pass system operation information to the ground for automated health monitoring. This is already routinely done routinely for engine data but may be expanded to encompass all critical aircraft systems in real time. System information will be monitored for significant deviations from normal on the ground. In the event of a non-normal situation being detected ground-based automated systems and engineering staff will evaluate the system failure and either provide advice to the pilot or re-configure the system remotely. Emphasis will be upon stabilising the situation and evaluating consequences rather than attempting to rectify the problem in flight.

In the event of a serious system failure, the implications for the continuation of the flight will be evaluated. If it is necessary to perform an immediate descent or diversion the appropriate navigation/flight planning facility will be notified.

Engineering support will be provided by engineers qualified on the aircraft and trained to provide remote real-time support in the advent of an airborne system malfunction.

Navigation/Flight Planning Support This is an extension of the existing airline flight planning functions to encompass real-time, in-flight planning/re-planning facilities. This facility will be expanded to encompass an 'aircraft-centric' point of view and be able to access the on-board flight management computers to up-link new routing information. Support (long and short term) will be provided by flight planning specialists.

System 'Mirror'

The system mirror will be an independent, ground-based (software) representation of the aircraft system states (in particular the Flight Management System (FMS); autopilot system and autothrust systems and the general configuration of the aircraft – flaps, slats etc.). Ground based system elements (pilot support station; flight/navigation panning and engineering support) will be able to interact with the ground-based system mirror without directly affecting aircraft systems (if required). In the advent of a datalink failure the system mirror will contain the last known configuration of the aircraft systems and will be able to update aircraft systems, if required. During normal operations the automation mirror will normally be 'transparent' all operators in the system.

MODELLING AND ANALYSIS OF SYSTEM CONFIGURATIONS

Complex socio-technical systems (such as flight operations) are made up of numerous interacting parts, both human and non-human, operating in a dynamic, ambiguous and safety critical domain (Harris and Stanton, 2010). The complexity embodied in these systems presents significant challenges for modelling and analysis, and requires Systems Ergonomics methods for the effective design of future work systems (Wilson and Carayon, 2014). Cognitive Work Analysis (CWA) is a structured framework specifically developed for considering the development and analysis of such complex socio-technical systems (Rasmussen et al, 1994; Vicente, 1999; Jenkins et al, 2009). The framework leads the analyst to consider the environment the task takes place within, and the effect of the imposed constraints on the way work can be conducted. The framework guides the analyst through the process of answering the question of why the system exists and what activities can be conducted within the domain, as well as how these activities can be achieved and who can perform them, also identifying the competencies required. Recent case studies have been conducted in the assessment of risk associated with nuclear decommissioning (Walker et al, 2014) and command team activities in control of a submarine (Stanton and Bessell, 2014).

The analyses in this paper commence with a generic Cognitive Work Analysis (CWA) concerning the operation of various options for system configurations in a number of operating scenarios. These analyses are supplemented by a Social Network Analysis (SNA) which provides an indication of the resilience of the operational networks in each case (Diskell and Mullen, 2004; Baber et al, 2013). This approach has previously been used to examine the characteristics of terror cells (Kenney et al, 2013) and command (Walker et al, 2009) networks. These analyses can be used to examine options for the proposed distributed system architecture for the operation of a single crew aircraft. They also help to define more specific aspects of new on-board automation requirements for the single crew aircraft and the role of the Ground Support Station/Office.

Analyses commence with a 'conventional' baseline aircraft (Airbus A320 and variants) being flown by two crew followed by an analysis of the same aircraft being operated by a single pilot. Note that it is a certification requirement that all aircraft must be capable of being safely operated by a single crew member (FAR/CS 25.1523 – Minimum Flight Crew). These initial analyses were followed by a comparative analysis of four different configuration options for a single crew operated aircraft being operated as part of a distributed system. Four potential versions of single pilot flight operations are presented for comparison (as shown in Table 1) i.e. a single pilot aircraft (A); a single pilot aircraft with an additional pilot at a ground station who can be called upon at times of need (C); a single pilot aircraft with an automation mirror on the ground that cross checks the inputs and outputs independently of the aircraft automation (B); and a single pilot aircraft with an additional pilot at a ground station and also with an independent automation mirror (D).

Table 1. Comparison of four potential versions of single pilot flight operations

Four versions of the future		Pilot in Ground Station	
		NO	**YES**
Automation Mirror	**NO**	Single pilot aircraft (Option A)	Single pilot aircraft with additional pilot on the ground (Option C)
	YES	Single pilot aircraft with additional automation mirror on the ground (Option B)	Single pilot aircraft with additional automation mirror on the ground and additional pilot on the ground (Option D)

Material for undertaking the CWA and SNA was drawn from a number of sources, including operations manuals and standard operating procedures (Airbus Industrie, n.d.). These were complemented by a structured de-brief of an experienced qualified Test Pilot who was also type rated on a number of Airbus types (and is a training Captain for a major airline), who also helped to devise the various operating scenarios. The CWA material will be presented first, as the formative design of the future system alternatives. Much has been made of CWA as a formative approach (Vicente, 1999; Jenkins et al, 2009; Naikar, 2013) but little if seen in practice. CWA served as the basis for identifying the functional loading on agents in the system as well as providing the data for the SNA.

Cognitive Work Analysis (CWA)

In the first phase of CWA, the Abstraction Hierarchy (AH) is used to model the work domain as follows.

Work Domain Analysis (WDA)

WDA is the most commonly used component within CWA (McIlroy and Stanton, 2011) and it identifies the constraints on workers' behaviour that are imposed by the purposive and physical context, or problem space, in which workers operate (Naikar, 2006a). WDA is conducted at the functional, rather than behavioural level; it is used to define the environment within which the activity is conducted. WDA identifies a fundamental set of constraints on the actions of any system component, thus providing a solid foundation for subsequent phases of the development of the aircraft (McIlroy and Stanton, 2011). The abstraction component of the diagram models the same system at a number of levels; at the highest level the overall functional purpose of the system is considered, at the lowest level the individual components within the system are described. Generally, five levels of abstraction are used:

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

The Functional Purposes

The AH was created in both a top down and a bottom up fashion. First, the overall functional purpose of flight operations was specified. This is the reason why the system exists. These purposes are independent of time; they exist for as long as the system exists. In this case, it is to 'transport people and cargo safely from A to B' and 'increase shareholder dividend' (i.e. ensure that the aircraft was economic to operate). These purposes were represented as two nodes at the top of the WDA in Figure 1.

The Values and Priority Measures

The next stage of the construction was to consider the level below the functional purposes, the values and priority measures, as shown in Figure 1. Here, further constraints on the system were more explicitly listed; these were measures for determining how well the intended system achieved its functional purposes. In this case they were identified as 'maximise comfort of passengers' (in order to enhance the customer experience), 'minimise risk' (to keep the system as safe as possible), 'maximise aircraft utilisation' (to keep avoid storage costs and enhance revenue) and 'reduce operating costs' (to avoid wastage). The way that the future aircraft system is configured to meet these needs is likely to be heavily contextually dependant.

The Physical Objects

As previously stated a mixture of a top-down and bottom-up approach has been employed in this analysis. Moving down to the lowest level of the hierarchy, the physical objects within the system were listed. The boundaries of this analysis limited this list to the systems of direct relevance to the operation of a future single crew aircraft, rather than every single object. The boundaries of the analysis indicate the levels of fidelity applied here. In an attempt to keep the analysis manageable, the boundary has omitted individual system elements. Whilst it would have been possible to decompose many of the listed objects into their component parts and describe their affordances more concisely this was outside the remit of this initial evaluation. A list of the physical objects analysed can be found at the base of Figure 1. This list comprises: primary flight display; navigation display; engine indication; anti-ice system; environmental conditioning system; electrical systems; fuel system; hydraulics; auxiliary power unit; flight management system; nav/comms (navigation/communication); throttle; rudder pedals; high lift devices; landing gear; brakes; fire extinguishing system and external lighting.

The Object Related Processes

The second level from the bottom of the AH, the object related processes, captures the processes that are conducted by the physical objects to perform purpose related functions. Most importantly, they capture the affordances of the physical objects independently of their purpose. For example, movement of the aircraft on the ground is afforded by the combination of the throttle, landing gear (nose wheel steering) and brakes. A complete list of the object related processes can be found at the level above the base level of Figure 1 along with the links indicating to which object they relate. To aid readability this list comprises: attitude of aircraft, airspeed; altitude of aircraft; rate of climb or descent; Instrument Landing System (ILS) indications; current heading of aircraft; flight plan; collision avoidance; terrain display; weather alerting; groundspeed; engine thrust; weight and balance of aircraft; engine health; prevent icing; maintain breathable atmosphere; maintaining thermal comfort; powering aircraft avionics; fuel management; management of hydraulics; communication management; performance/cost index; movement of aircraft on the ground; safety of cargo; and conspicuity of aircraft.

The Purpose Related Functions

In the middle of the AH, the purpose related functions are listed. These functions have the ability to influence one or more of the values and priority measures. They link the purpose-independent processes with the object-independent functions. They are listed as: aviate (i.e., keeping the aircraft airborne); communicate (i.e., staying in touch with ATC/ATM, company operations as well as communicating with crew and passengers); navigate (i.e., plan, change and check the route for the aircraft as required); manage (i.e., manage the avionics system) and warn (i.e., indicate to aircrew and company operations when system are outside their tolerances).

The use of the means-ends-links and the utility of the AH can be described with the example shown in Figure 1. Figure 1 shows the node 'aviate' in the purpose related functions level. Following the links out of the top of this node, answers the question 'why is this needed?' - in this case to 'maximise comfort of passengers' and 'maximise aircraft utilisation'. Following the links down from the 'aviate' it is possible to answer the question 'how can this be achieved?' - in this case by 'attitude of aircraft'; 'airspeed'; 'altitude of aircraft'; 'rate of climb'; ILS indications' and 'current heading/track of aircraft'.

The diagram does not prescribe a particular arrangement for providing this functionality, rather it lists all of the components that can affect it. In this case, there is redundancy in the system.

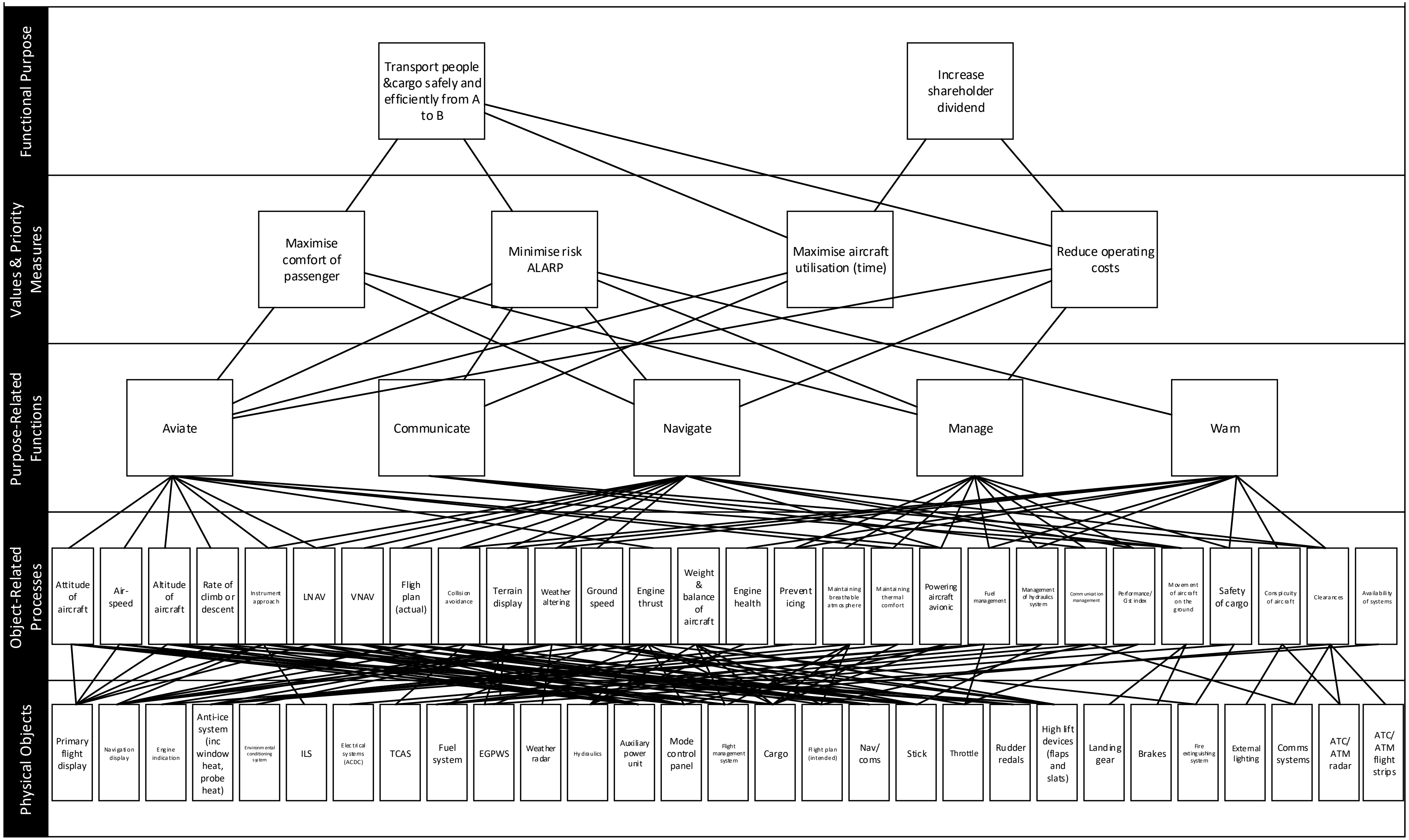


Figure 1. Work Domain Analysis showing the five levels and the means-ends-links

Control Task Analysis (ConTA)

The second phase of the CWA framework, Control Task Analysis (ConTA), allows the requirements associated with known, recurring classes of situations to be identified. Naikar et al (2006a, 2006b) have developed the contextual activity template (see Figure 2) for use in this phase of the CWA. This template is one way of representing activity in work systems that are characterised by both work situations and work functions. Work situations can be decomposed based on recurring schedules or specific locations. Rasmussen et al (1994) describes work functions as being activity characterised by its content independent of its temporal or spatial characteristics. These functions can often be informed by the abstraction hierarchy. Rasmussen et al (1994) recommend that the analyst decompose on either work functions or work situations; however, Naikar et al (2006a, 2006b) plot these on two axes so that their relationship can be investigated, allowing the representation of activity in work systems that are characterised by both work situations and work functions. Typically, the work situations (in this case the phases of flight as defined by the International Civil Aviation Organization: ICAO) are shown along the horizontal axis and the work functions (associated with controlling and managing the aircraft) are shown along the vertical axis of the Contextual Activity Template (CAT). The circles indicate the work functions with the bars showing the extent of the table in which the activity typically occurs. The dotted boxes around each circle indicate all of the work situations in which a work function can occur (as opposed to must occur) thus, capturing the constraints of the system. Figure 2 shows the CAT for the purpose related functions derived from the abstraction hierarchy (see Figure 1). The situations follow the main phases of flight operations from the aircraft standing at a gate to landing on a runway (assuming that taxiing and standing will be similar for both take-off and landing) along with the addition of an emergency descent.

Looking at Figure 2, perhaps the most salient feature is that in an aircraft during flight operations, some function constraints are notably contextually influenced (e.g. rate of climb or descent, terrain display, ground speed, and movement of aircraft on the ground) whereas others are not (e.g., engine thrust, engine health, powering aircraft avionics, management of hydraulics and communication systems). To read Figure 2, note that an empty cell means that the function (vertical axis) cannot be performed in that situation (horizontal axis); a dashed box means that the function *can* be performed in the situation, and a ball-and-whisker means that the function is *typically* performed in the situation.

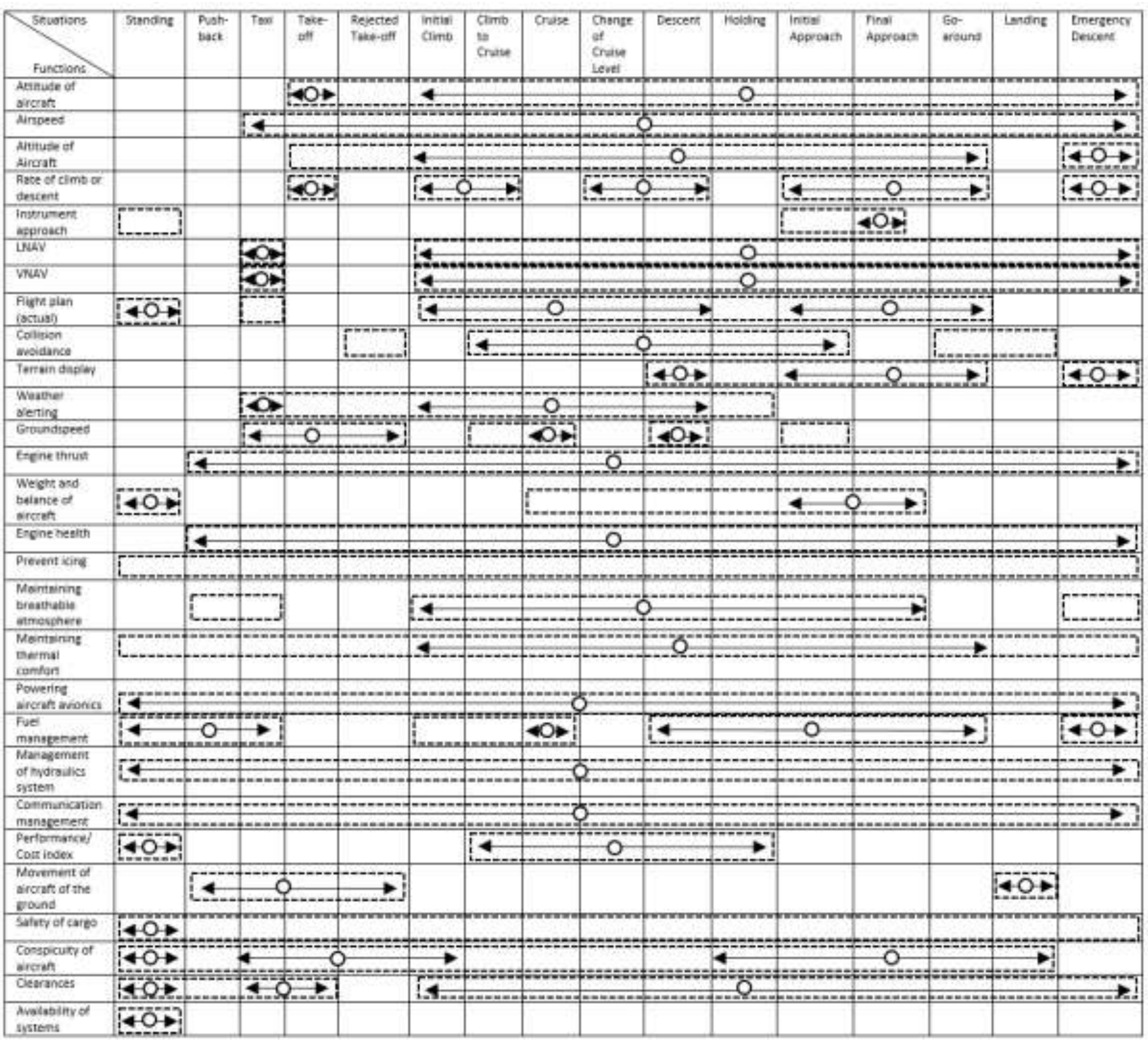
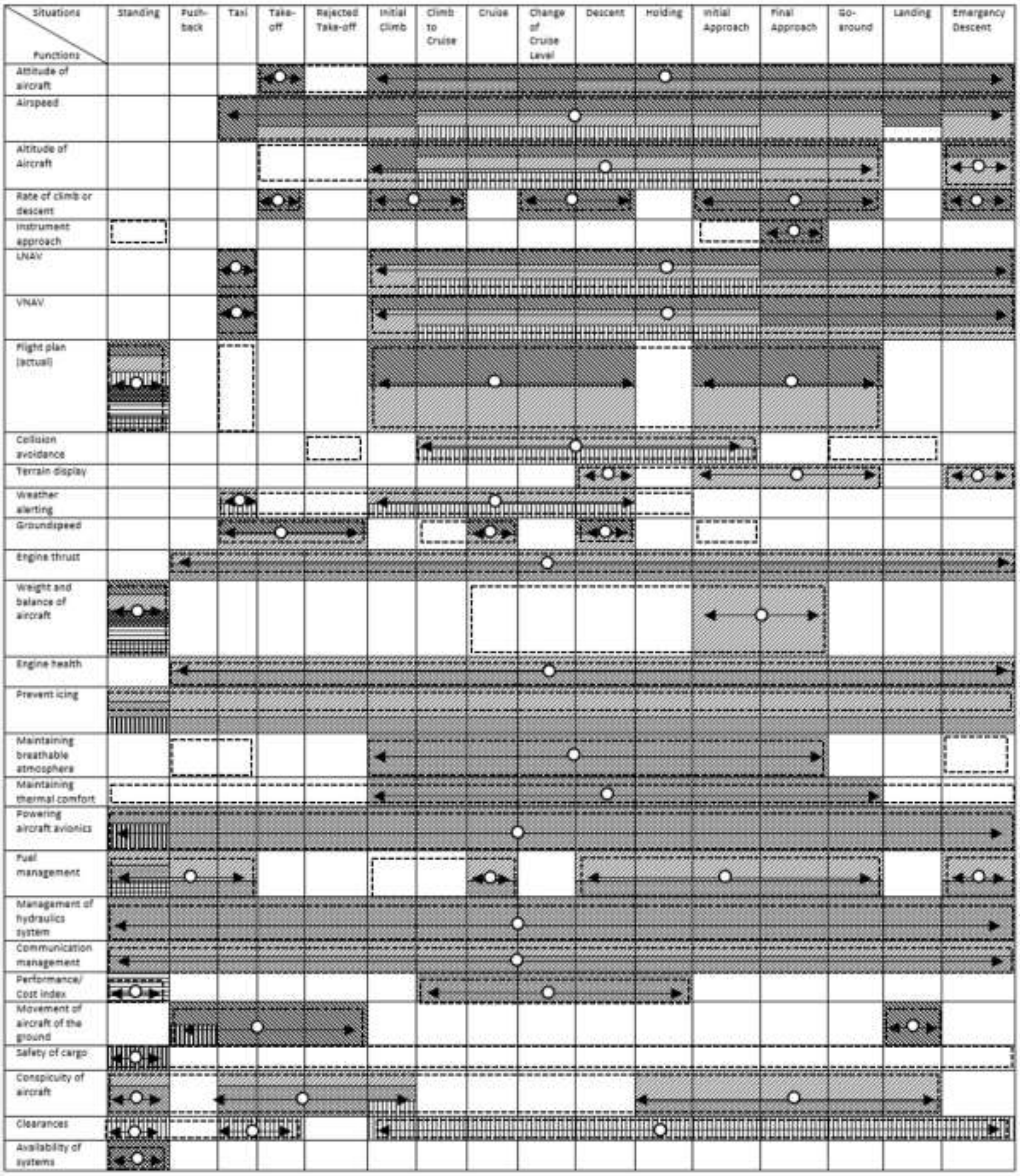


Figure 2. Contextual Activity Template for object-related processes

Social Organisational Cooperation Analysis – Contextual Activity Template (SOCA-CAT)

In the next phase of the analysis, roles of personnel are allocated to the functions across the situation. This phase is called Social Organisation and Cooperation Analysis – Contextual Activity Template (SOCA-CAT). A list of the key roles and their related coding can be seen in Figure 3. One of the roles is non-human, denoted as Aircraft Automation in Figure 3 (the light speckled coding).



Pilot Flying	
Pilot Monitoring	
Aircraft Automation	
ATC/ATM	
Dispatch	
Flight Planning	
Engineering	
Ground Handling	
Fuelers	

Figure 3. Social Organization and Cooperation Analysis Contextual Activity Template (SOCA-CAT) for current flight operations

As Figure 3 shows, many of the functions in the baseline aircraft are performed either exclusively by, or with the assistance of automation. There is a clear demarcation between the roles of the pilot flying (red coding) and the pilot monitoring (green coding). The pilot monitoring is oversight of the pilot flying (red coding), automation (blue coding) and ATC/ATM (pink coding). It is striking that each function tends to be assigned to the same set of roles throughout all situations (where that function applied). Of the 25 functions identified, 10 are typically the responsibility of just a single agent, whereas 15 are joint responsibility (most of which are the responsibility of two agents). Some 240 of the 400 cells (functions against situations) have been assigned to agent roles in the Social Organisation and Cooperation Analysis Contextual Activity Template (SOCA-CAT).

SOCA-CAT has provided the data for building the social networks. This method has previously been proven by Baber et al (2013) when developing operational concepts for Search and Rescue missions. In essence, every within cell and between cell relationship becomes a link between agents in the network (except for the emergency descent). In this way it is possible to step from a formative allocation of function to a formative social network analysis. This is a useful extension of the CWA framework, as it enable quantitative as well as qualitative exploration of future operational concepts.

Social Network Analysis

Social Network Analysis (SNA) is used to analyse and represent the relationships between agents and artifacts within a network. A social network is defined as a set or team of agents that possess relationships with one another (Driskell and Mullen, 2004). In this case the social network extends beyond the aircraft to other agencies such as air traffic control; fuellers; dispatch etc. With changes in automated support on the ground and in the air, coupled with increases in air traffic density, aircraft operational concepts are constantly changing. Direct routing and self-assured separation ('free flight') have vastly expanded the Joint Cognitive System boundaries around airliner operations well beyond the flight deck (Hollnagel, 2007). SNA is based upon the notion that the relationship between agents within a social network has a significant effect upon the actions performed and also the performance achieved by the network. SNA uses both graphical and mathematical procedures to represent social networks. Typically, centrality measures are calculated for each agent (e.g. degree, betweenness and closeness) and the overall network density is calculated. This allows the identification of the key agents within the network and also the classification of the network structure. The technique has previously been used for the analysis of networks in a number of areas, such as command and control (Stanton, Baber and Harris, 2008), search and rescue operations (Baber et al, 2013) and submarine command teams (Stanton, 2014). All three studies have shown those people (agents) who are most important to the success of the team, based on communication frequencies. There are a number of metrics associated with the analysis of whole networks, depending upon the type of evaluation that is being performed. The size of the network determines the number of possible relations, and the number of possible relations grow exponentially with the size of the network. This defines the network's complexity. The latter is expressed in the form of social relations that are actually observed represented as some fraction of the total possible.

A major advantage of networks is that they do not differentiate between different types of node (e.g., artefacts and/or people), so that from a modelling perspective they are not constrained by existing structures, but rather help to define the tasks allocation associated with a particular scenario (Baber et al, 2013; Stanton, 2014). It is also possible to model the temporal aspects of networks by identifying critical moments in the sequence of activity. To do this the scenario is divided into task phases allowing active and non-active elements to be specified and represented.

The first step in a SNA involves defining the network that is to be analysed. Once the overall aircraft operation network is specified, the people and/or artefacts need to be defined. In the case of the development of the single crew aircraft a number of different networks were identified for analysis over a number of different flight scenarios. In this case the agents identified were: the pilot flying; the pilot monitoring; air traffic control and air traffic management; dispatch; flight planning; engineering; ground handling and the fuelers. For comparison, a description of current operations of two crew flying the baseline aircraft is provided (see table two) against which the envisaged single crew commercial aircraft options are contrasted. The initial analyses pertain to aircraft operations as a whole, not to any particular normal, non-normal or emergency situation. The matrix represents the frequency of associations between each agent in the network. This matrix shows whether or not an agent within the current aircraft system of operation can be associated with any other agent in the proposed architecture for the single crew aircraft, specifically through frequency of communications. As an example, the association matrix for the generic aircraft operational scenario is presented in Table 2.

Table 2. Association Matrix for Baseline Aircraft Generic Operational Scenario

Network Agents: from/to	**PF**	**PM**	**AA**	**ATC/ ATM**	**D**	**FP**	**GH**	**F**
Pilot Flying (PF)	-	62	12	33	2	2	2	2
Pilot Monitoring (PM)	62	-	82	48	2	2	2	4
Aircraft Automation (AA)	12	82	-	2	0	0	4	2
ATC/ATM	33	48	2	-	1	2	0	0
Dispatch (D)	2	2	0	1	-	2	0	0
Flight Planning (FP)	2	2	0	2	2	-	0	0
Ground Handling (GH)	2	2	4	0	0	0	-	0
Fuelers (F)	2	4	2	0	0	0	0	-

An example social network diagram for the takeoff task is presented in Figure 5. Comparison with the network archetypes shows that the network is mesh-like, with dispatch and flight planning on the left-hand side, pilot monitoring, ATC/ATM and pilot flying in the middle and ground handling, aircraft automation and fuelers on the right-hand side. Mesh structures are considered to be generally robust (Stanton, Baber and Harris, 2008).

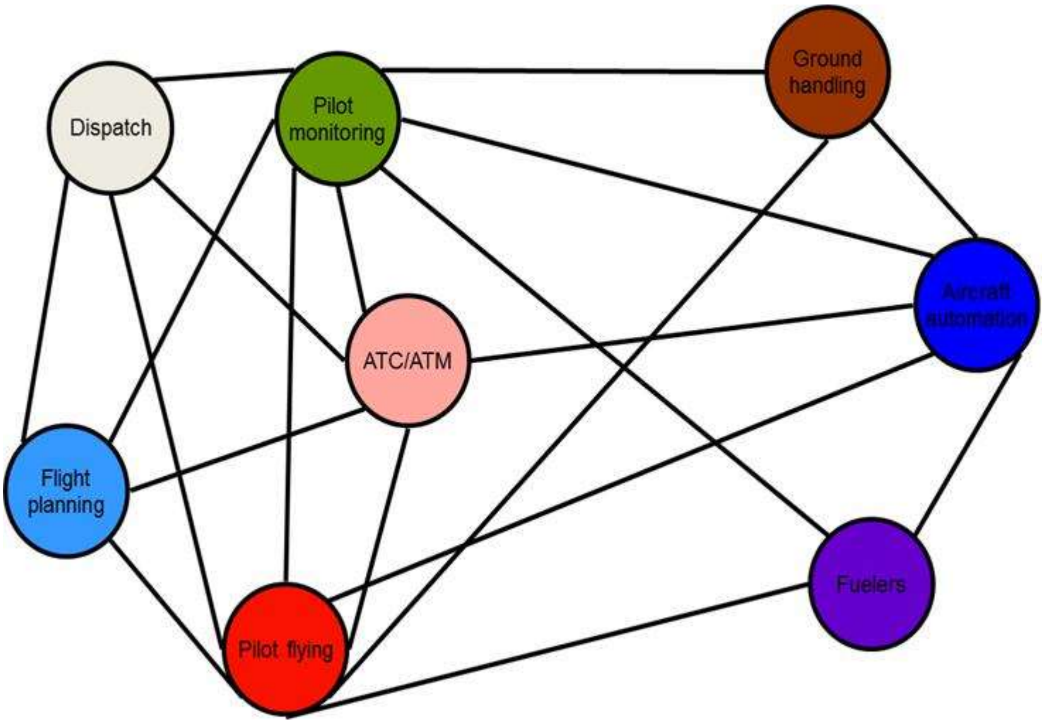


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Figure 5. Network Diagram for Baseline Aircraft Generic Operational Scenario

Counting the number of collaborative (i.e. within cell) and cooperative (i.e. between cells) links gives rise to the data presented in Table 2 (which assumes a symmetrical network, with every link reciprocated, such as with a read-back or acknowledgement of each and every communication). This network forms the basis for the numerical analysis using SNA statistics (see Table 3). Theses statistics can either look at the network as a whole (e.g., the density of a network is defined by the number of social relations that are actually observed and can be represented as some fraction of the total possible) or analyse the individual nodes, e.g.:

- **Emission** and **reception** degree are the number of ties emanating from, and going to, each agent in the network.
- **Eccentricity** is defined by the largest number of hops an agent has to make to get from one side of the network to another.
- The **sociometric status** of each agent refers to the number of communications received and emitted, relative to the number of nodes in the network.
- Agent **centrality** is calculated in order to determine the central or key agent(s) within the network. There are a number of different centrality calculations that can be made. For example, agent centrality can be calculated using Bavelas-Leavitt's index.
- **Closeness** is the inverse of the sum of the shortest distances between each individual and every other person in the network. It reflects the ability to access information through the 'grapevine' of network members.

- **Farness** is the index of centrality for each node in the network, computed as the sum of each node to all other nodes in the network by the shortest path.

- **Betweeness** is defined by the presence of an agent between two other agents, which may be able to exert power through its role as an information broker.

The same principles were used to develop the four networks associated with each of the single pilot options, each representing one of the four visions for future flight operations. Again, the networks appeared mesh-like, with fewer connections in the network in Option A (single pilot aircraft) and more connections in Option D (a single pilot aircraft with an additional pilot at a ground station and also with an independent automation mirror).

Table 3. Social Network Analysis statistics

Nodal statistics	**PF**	**PM***	**AA**	**ATC ATM**	**D**	**FP**	**GH**	**F**
Emission/Reception	115	**202**	102	86	7	8	8	8
Eccentricity	1	**1**	2	2	2	2	2	2
Sociometric Status	25.55	**44.88**	22.66	19.11	1.55	1.77	1.77	1.77
Centrality (B-L)	5.28	**5.28**	4.11	4.11	3.70	3.70	3.36	3.36
Closeness	1.28	**1.28**	1.00	1.00	0.90	0.90	0.82	0.82
Farness	7	**7**	9	9	10	10	11	11
Betweeness	7.33	**7.33**	2.00	1.33	0	0	0	0

*bold highlighting of possible role to be displaced to a ground station

More robust networks generally have more connections, but that does not necessarily mean that everything should be connected to everything else. Unnecessary connections in a network can lead to greater coordination problems and could also mean that irrelevant information is being communicated (Rafferty et al, 2012; Sorensen and Stanton, 2013). Analysis of the SOCA-CATs shows some differences in the functional loading of the single pilot configurations compared to the current version of flight operations, as revealed in Table 4.

Table 4. Functional loading for the Generic Scenario

Function Loading/Options	**Current system**	**Option A**	**Option B**	**Option C**	**Option D**
Pilot Flying (PF)	90	217	217	90	90

Pilot Monitoring (PM) or Pilot on the Ground (PG)	160	-	-	160	160
Aircraft Automation (AA)	143	143	143	143	143
System Mirror (SM)	-	-	143	-	143
Air Traffic Control (ATC) and Air Traffic Management (ATM)	51	51	51	51	51
Dispatch (D)	2	2	2	2	2
Flight Planning (FP)	3	3	3	3	3
Ground Handling (GH)	4	4	4	4	4
Fuelers (F)	3	3	3	3	3
Network Density*	0.422	0.266	0.377	0.422	0.555

*Network density is calculated as a fraction of total possible connections in the network.

As Table 4 shows, removing the pilot monitoring from the network dramatically increases the functional loading on the remaining pilot on the flight deck as well as reducing the density of the network (where 0 means no connections and 1 means everything is connected to everything else). The single pilot with a pilot on the ground (Options C and D) has the closest resemblance to current operations (although the pilot on the ground would have responsibility for monitoring several aircraft in different phases of flight). This comparison is for both the loading of functions and the network density. The most robust network appears to be option D, with the single pilot with the pilot on the ground and the automation mirror (which replicates the aircraft automation, using the same inputs and comparing with the results of the aircraft automation – only reporting when a discrepancy is found), as this network has the highest density (Walker et al, 2009)

The SOCA-CAT cooperation and collaboration interactions were compiled for comparative analysis. As before, the analysis assumes that the networks were symmetrical, that each input is met with a corresponding output. For human-human interaction this would mean that a request is met with a response or that an instruction is met with confirmation (this could be verbal or non-verbal, such as moving a lever which is seen by the person issuing the instruction). In human-machine interaction this would mean that depressing a switch or typing an instruction into the automation is met with some form of output such as a change in the display status or direct voice output.

Table 5. Social network analysis of the four future concepts

OPTION A	PF	AA	ATC ATM	D	FP	GH	F
Emission/Reception	151	102	52	5	6	6	6
Eccentricity	1	2	2	2	2	2	2
Sociometric Status	33.55	22.66	11.55	1.11	1.33	1.33	1.33
Centrality (B-L)	5.00	3.75	3.75	3.33	3.33	3.00	3.00
Closeness	1.5	1.15	1.12	1.00	1.00	0.90	0.90
Farness	6	8	8	9	9	10	10
Betweeness	13	3	2	0	0	0	0

OPTION C	PF	PG	AA	ATC ATM	D	FP	GH	F
Emission/Reception	115	202	102	86	7	8	8	8
Eccentricity	1	1	2	2	2	2	2	2
Sociometric Status	25.55	44.88	22.66	19.11	1.55	1.77	1.77	1.77
Centrality (B-L)	5.28	5.28	4.11	4.11	3.70	3.70	3.36	3.36
Closeness	1.28	1.28	1.00	1.00	0.90	0.90	0.82	0.82
Farness	7	7	9	9	10	10	11	11
Betweeness	7.33	7.33	2.00	1.33	0	0	0	0

OPTION B	PF	AA	SM	ATC ATM	D	FP	GH	F
Emission/Reception	245	204	204	54	5	6	10	8
Eccentricity	1	2	2	2	2	2	2	2
Sociometric Status	54.44	45.33	45.33	12.00	1.11	1.33	2.22	1.77
Centrality (B-L)	5.57	4.33	4.33	4.33	3.54	3.54	3.54	3.54
Closeness	1.28	1.00	1.00	1.00	0.81	0.81	0.81	0.81
Farness	7	9	9	9	11	11	11	11
Betweeness	14	2	2	4	0	0	0	0

OPTION D	PF	PM	AA	SM	ATC ATM	D	FP	GH	F
Emission/Reception	127	284	204	204	88	7	8	12	10
Eccentricity	1	1	2	2	2	2	2	2	2
Sociometric Status	28.22	63.11	45.33	45.33	19.55	1.55	1.77	2.66	2.22
Centrality (B-L)	5.87	5.87	4.7	4.7	4.7	3.9	3.9	3.9	3.9
Closeness	1.12	1.12	0.9	0.9	0.9	0.75	0.75	0.75	0.75
Farness	8	8	10	10	10	12	12	12	12
Betweeness	8.16	8.16	1.5	1.5	2.66	0	0	0	0

KEY: single pilot (top left – Option A), single pilot with system mirror on the ground (bottom left – Option B), single pilot with additional pilot on the ground, (top right – Option C) and single pilot with additional pilot on the ground and system mirror on the ground (bottom right – Option D).

The analysis of the networks across the various metrics confirm that the two networks on the right hand side of the figures (i.e. the single pilot with additional pilot on the ground - top right- Option C) and single pilot with additional pilot on the ground and automation mirror on the ground (bottom right- Option D) are the most robust versions of the network as there is less dependency on the single role at the centre of the network (i.e. the pilot flying). This is revealed in several ways. First the eccentricity of the nodes in the network (i.e. the largest number of hops an agent has to make to get from one side of the network to the other) where the pilot flying and the pilot on the ground have only one hop in the version on the right-hand side of the figure, making them all-connected in the terms of the network archetypes (as shown by the number of ties). The pilot on the ground has the highest nodal degree and sociometric status on the right-hand side of the figure, which is due in part to the number of ties and in part to the greatest number of emission and reception connections with other nodes in the network. The pilot flying and the pilot on the ground are highest on the centrality and closeness metrics because they are both at the centre of the network and have the shortest distance to every other node. This suggests that they have high importance in the network, which is not very surprising (Baber et al, 2013; Harris et al, 2015; Kenney et al, 2013). They are also lowest on farness for the same reasons. On the betweenness metric the pilot flying exerts less influence over the network because this influence is shared with the pilot on the ground. The combination of more links and less dependency on any one agent makes for a more robust network (Stanton, 2014). In summary, SNA can be used to determine the importance of different agents within a social network and also to classify the network type. SNA offers a comprehensive analysis of the network in question. The key agents within the network are specified, as are the frequency and direction of communications within the network. As such it proves useful for comparing the different networks that result from the new single pilot concepts.

As a development of method, the relationships between CWA and SNA are not necessarily obvious but have allowed novel exploration of the differences between dual, single and distributed crewing options in this paper. To that extent we have further developed the approach reported by Houghton et al (2006) and Baber et al (2013). The SOCA-CAT phase of CWA offers a formative allocation of functions against situations (phases of flight in the present case). As such it has enabled us to consider the possible communications between the agents in the system for all four of our proposed options against the current dual crewing operations. As safety is paramount in aviation, we require any future option to be as least as safe as contemporary crewing. SNA offers the opportunity to consider the likely effects on the communication networks from a quantitative perspective.

CONCLUSIONS

Previous approaches to develop a single-crew aircraft have focused on the development of sophisticated airborne technology to assist the pilot but have achieved only mixed success (Harris, 2007). However, there are no major reasons why a single pilot operated commercial aircraft is not feasible in the very near future using existing technology. Military aviation has flown complex, high performance, single crew aircraft for many years and Uninhabited Air Vehicles are now commonplace. It is time for these technologies to be spun-out further into the commercial domain where they may be applied to financial advantage. The greatest obstacle to the operation of civil, single pilot, aircraft is not the technology per se. It is combining the technology, designing the user interfaces and developing a new concept of operations to make such an aircraft safe and useable in a wide range of normal and non-normal operating situations when flown by a typical commercial pilot. The Human Factors requirements are the prime driver in this case, not the technology (Harris, 2007).

Instead of developing a concept of single-pilot operations based upon equipping an aircraft with complex automation to aid the pilot, the approach described in this paper begins to demonstrate how by using a distributed, air/ground, socio-technical system, such an aircraft could be ready for service entry within a decade. Instead of replacing many of the functions of the second pilot, they are simply displaced to assistance on the ground (q.v. the operation of UAVs). Furthermore, in many circumstances the assistance provided from the ground may be of higher quality and better targeted than that normally available from the second seat on the flight deck, as a result of being able to draw upon a wider range of engineering and flight planning resources.

Cognitive Work Analysis, especially the SOCA-CAT phases has been useful as a formative system design approach to help understand the function allocation distribution between the agents and the functional loading on them. Extending this analysis to understand communication interactions in SNA has revealed option D (single pilot with additional pilot on the ground and system mirror on the ground) as the most resilient, even more than the current dual pilot cockpit. It is debatable whether or not this option could have prevented the recent tragedy with German Wings (BBC, 2015), which has revealed a further weakness with current operations. Nevertheless, it is most likely that reduced crewing options are most likely to be implemented in short-haul cargo operations before they ever become a possibility for passenger carrying aircraft.

The baseline descriptions for general operations of a conventional two-crew airliner (using CWA and SNA) and the same airliners being operated by just a single crew member give an overall idea of the level of complexity and resilience in the current system that need to be achieved in future single crew operations. There is a natural split between the PF and PM functions that have evolved over decades. The main question being addressed here is: do these roles have to be co-located? In particular the CWA and SNA describe the functions required irrespective of their location. The social network statistics produced for the various configurations of single crew operations indicate that equivalent (or even enhanced) levels of system resilience may be achieved.

Future research will extend the analysis into contemporary issues such as trajectory, conflict and system-wide information management. Another important goal of this research is to validate the SOCA-CAT and SNA models in flight simulators. This would require developing the scenarios and structures as presented in the four options and testing against the baseline with pilot crews. This analysis would also enable experiential feedback from pilots to be gathered to supplement the performance data, offering and opportunity to understand how alternative crewing option might affect the duty of care to the pilots have for the passengers that they are carrying. The immediate future of the flight deck is unlikely to change dramatically, but we can foresee a time within the next twenty years when the distributed crewing concept could enter short-haul cargo operations. When this is proven to be safe and effective it might even enter into service for short haul passenger aircraft.

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