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Constraint analysis for aircraft landing in distributed crewing contexts

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Abstract

The aim of this paper is to analyze human factors related and methodological constraints that prevent the distributed crewing or single pilot operational concept to be pushed forward in commercial aviation. First, it has been argued that alternatives for current commercial flight operations are not necessarily constrained by technology, but by the human factors characteristics of the socio-technical systems enabling these operations. In this paper, we present a constraint analysis of the landing phase of flight (both manual and automatic) using Cognitive Work Analysis (CWA). Given that CWA enables linking constraints related to human and non-human elements of the system and their interactions, CWA supports exploring systemic design solutions for distributed crewing operation. We argue that automatic landing calls for designing for distributed situational awareness, whereas manual landing calls for designing novel human roles in the overall system. Second, distributed crewing concept is being researched by several research groups simultaneously and with various methodologies, including expert interviews, semi-structured task analysis, experiments, policy and historical analysis. In the second half of the paper we argue that successfully progressing towards distributed crewing will require collaboration between research groups and integrating findings obtained with mixed methods. We explore strategies for mixed-method integration in the context of designing distributed crewing operations.

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1. Introduction

Single Pilot Operations (SPO) or Distributed Crewing Operations (DCO)[1] mean re-designing the aviation system in a way that one of the pilots is replaced with additional ground personnel. It has been argued by [1] that alternatives for current commercial flight operations are not necessarily constrained by technology, but by the human factors characteristics of the socio-technical systems enabling these operations. Sections 2-4 present an analysis of the human factors constraints that impede the progression towards SPO. Among other things, SPO will change the coordination between actors, task distribution, and communication with ATC [2]. Providing detailed design specifications in context of the SPO concept of operations (CONOPS) requires that the perspectives of actors and that of the whole system are taken into account simultaneously.

Sections 2-4 present a constraint analysis of landing, which is one of the busiest airborne phases of flight using Cognitive Work Analysis (CWA) [3]. CWA is a method that enables the joint consideration of the above mentioned perspectives. Section 5 presents initial design recommendations for SPO based on the CWA of landing. Section 6 presents initial considerations for overcoming a methodological constraint that hampers the progression towards SPO. In particular, success in designing SPO calls for solutions to integrate findings obtained by remote research groups and with diverse methodologies. First, successfully designing and implementing SPO requires collaboration between the growing number of research groups and projects that investigate SPO e.g. in terms of drawing design recommendations based on results obtained by remote research groups. Second, in order to evaluate the effect of changes that SPO would impose, aviation performance needs to be studied from heterogeneous perspectives and with mixed methodologies. Relevant perspectives include task distribution and coordination between actors [2], regulatory and stakeholder analysis [4] alongside with flight deck [5] and ground station design [6] in the SPO context. In order to track system level interdependencies and to overcome reductionism [7] these perspectives need to be considered simultaneously. Relevant methods include semi-structured task analyses, expert interviews, experimental design and regulation analysis.

2. Cognitive Work Analysis

Cognitive work analysis (CWA) allows the analysis, design and qualitative prediction of complex socio-technical system performance. Conceptually, CWA is grounded in an ecological approach to cognition. It conceptualizes skilled performance as functional system performance where the actor and the 'context' constitute a functional unit. Hence, CWA enables taking the perspective of actors and the system into account simultaneously. Characteristics of performance are explained with the help of performance shaping constraints. Functional performance is understood to emerge as the result of constraints reducing the degrees of freedom of the system. CWA conceptualizes five types of ('layers') of constraints (performance shaping factors) that equal to five phases of analysis:

1. Work Domain Analysis (WDA) allows identifying the constraints imposed by the work domain.
2. Control Task Analysis (CAT) enables identifying the requirements associated with expert action associated with known classes of events in a particular domain.
3. Strategies Analysis enables understanding the different ways in which activities identified in subsequent sections can be accomplished.
4. Social Organisation and Coordination Analysis (SOCA) enables identifying the constraints imposed by the social and organisational characteristics of the system.
5. Worker Competencies Analysis enables identifying the competencies that each actor roles should exhibit.

We have focused on the WDA, CAT, and SOCA of one of the busiest phases of flight, landing – both manual and automatic. The WDA outputs an abstraction hierarchy (AH), a tree based structure defined on 5 levels:

1. Functional purpose level defines the overall purpose of the system.

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[1] In this paper we use the SPO and DCO terms interchangeably.

2. Values & priorities level represent values that constrain the way the functional purpose is achieved in the domain under analysis.
3. Purpose related functions level links affordances to functional purposes. These represent constraints that are embodied by physical objects and imposed by the functional purpose of the system.
4. Object-related processes level defines the affordances granted by the objects in the functional systems defined by the functional purpose.
5. Physical objects level defines the objects that have functional roles in the system under analysis.

CAT addresses system activities in terms of the situation in which they are or can be performed [8]. CAT can be represented as a two dimensional matrix where the horizontal axis is populated by situations that can be defined temporally, spatially or the combination of the two; and the vertical axis can be composed by either object-related processes or purpose-related functions. Empty cells indicate situations where the function is not possible. Cells in which ball and whiskers are displayed indicate the situations where functions that can and typically do occur. Cells surrounded by dashed line indicate situations where the function could but typically do not occur. [8] By differentiating between these conditions, flexible and rigid boundaries can be identified. Flexible boundaries indicate design possibilities for removing current system constraints; whereas rigid boundaries indicate boundaries for functioning that cannot be changed.

SOCA enables depicting the distribution of activities between actors in the system, hence analysing the constraints imposed by social and organisational structures and actor roles. Actors can include both human and non-human actors (e.g. automation). SOCA enables analysing the cooperation and communication between actors. In our analyses we represented SOCA-CAT with the tool developed by [9].

3. Cognitive Work Analysis for manual landing

When the destination airport does not have ILS facilities, or if the aircraft has a fault that prevents automatic landing to be performed, manual landing needs to be performed. In this section, we present the results of a CWA performed for the manual landing flight scenario. The present analysis was conducted with a set of assumptions that are presented below. Under different assumptions, the CWA and the constraints identified might change. The assumptions were identified with the aim to maximise the representativeness of the scenario analysed, and are as follows: a) object-related functions required for manual landing are working, b) state-of-the art technology (analysis was based on flight performance with Boeing aircrafts), c) state-of-the art operational context (not SESAR / NextGen).

3.1. WDA for manual landing

The purpose related function associated with the manual landing scenario is ''Landing the aircraft manually''. This is the purpose that values and priority measures, purpose related functions and objects (affordances) serve. As outlined in Section 2 values and priority measures characterise constraints imposed by the way the functional purpose is to be achieved in the system under analysis. Values and priority measures in manual landing include

a. Maximize time efficiency. Landing need to be coordinated in time according to schedules in order to enable continuous air traffic and avoid delaying other flight operations.
b. Maximize safety. While being time efficient, safe performance also needs to be ensured.
c. Adhere to social norms. Pilots are influenced by social norms due to the need for belonging and characteristics of group cognition [10]. Social norms are influenced by both company culture and ad-hoc norm formation in the cockpit team.
d. Adhere to SOP. Pilots need to respect the flight procedures imposed by the airline company.
e. Minimize discomfort. The discomfort of the passengers and the crew needs to be kept at an absolute minimum.
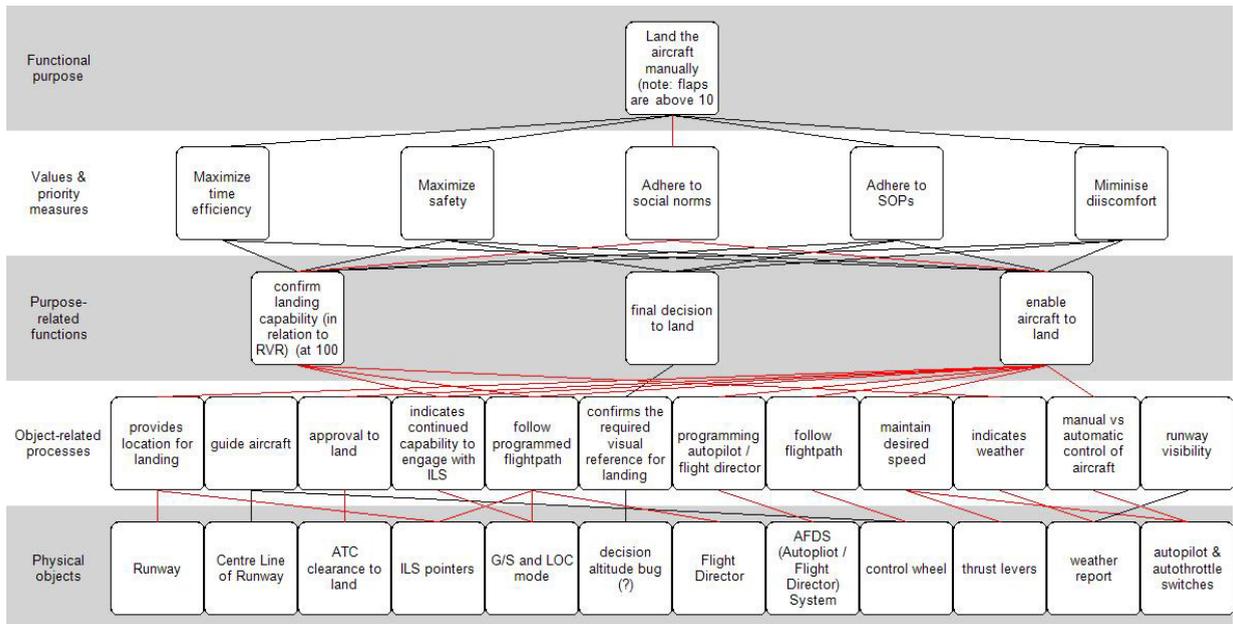
Fig. 1. Abstraction Hierarchy for Manual Landing.

The physical objects listed include the objects that have functional significance for manual landing. Affordances of the objects are presented at the object-related processes level. Some objects have more than one affordance which indicates that objects enable functional performance in multiple ways. For example, weather reports that both indicate weather and afford runway visibility. Purpose related functions include: confirm landing capability at 1000R, final decision to land, and enable aircraft to land.

3.1. SOCA-CAT for manual landing

Situations for the manual landing scenario were defined according to the temporal sequence of landing performance. Given the tight link between spatial and temporal changes in aviation performance, the situations also have spatial characteristics. However, in the present analyses the temporal perspective was granted priority because it is assumed that it is by enhancing temporal coordination of flight events, and the timely coordination between actors and information flows that flight performance can be improved. Spatial coordination is a specific task of ATC. The situations for manual landing are as follows: before top of descent, approach ban, decision height point, just prior to touchdown and touchdown. Functions were defined as object-related functions.

As it can be seen in Figure 2, there are a few flexible constraints in the state-of-art practices of manual landing. With suitable design solutions, flexible constraints could be removed and flight performance might be enhanced. Most importantly from the perspective of enhancing landing performance, approval for landing could be provided in a set of situations by ATC; and visual reference for landing could be confirmed earlier as it is done usually. This might be supported by suitable technology, such as eyes-out displays. However, as it can be seen in Figure 2, there is a set of rigid boundaries that need to be adhered to under all design solutions. These include following the flight path, maintaining desired speed and guiding the aircraft throughout landing. Moreover, visual reference for landing needs to be confirmed at the decision height point the latest. The rigid constraints imposed by these functions might inform design solution of system design in a distributed crewing context.
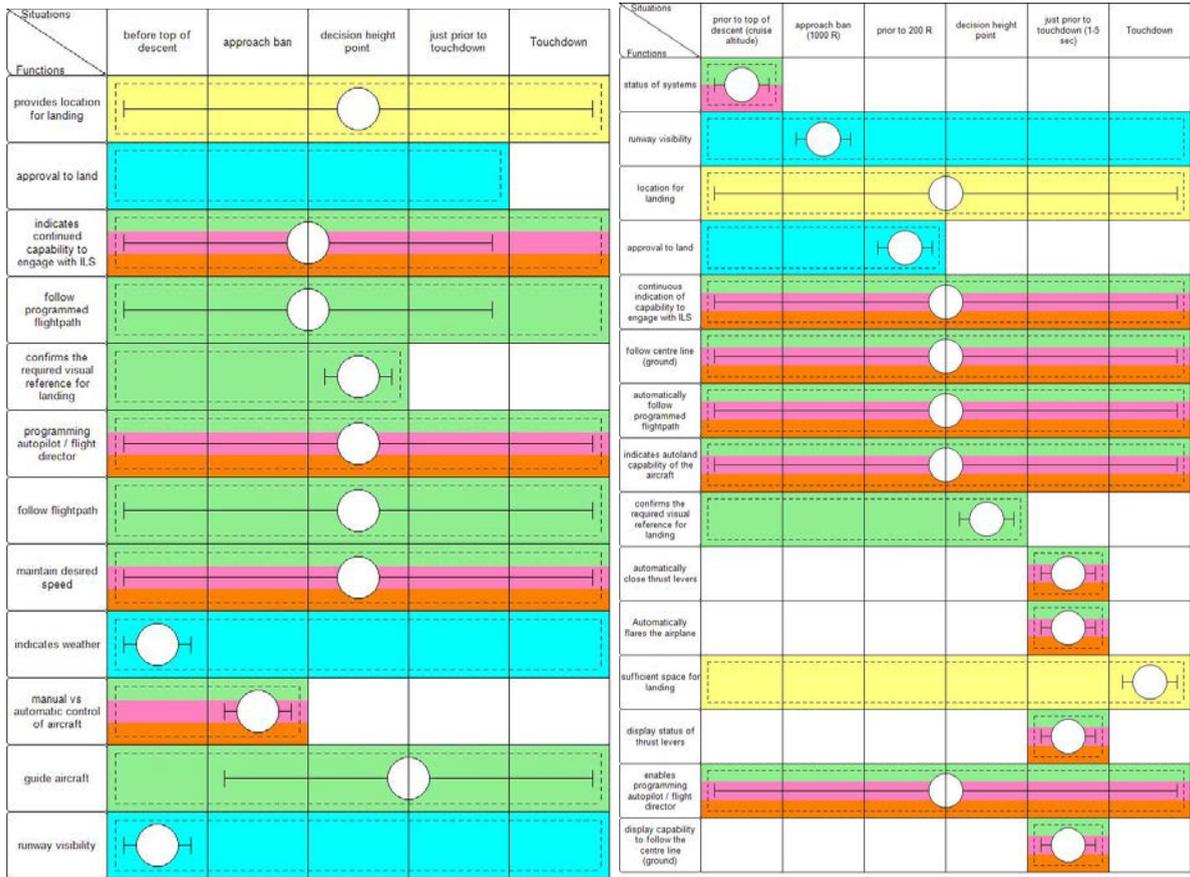
Fig. 2. (a) SOCA-CAT for Manual Landing; (b) SOCA-CAT for Automatic Landing.

4. Cognitive Work Analysis for automatic landing

In low visibility operations, with suitable ILS facilities available at the destination airport, automatic landings are necessary. In this section, we present the results of the CWA for the automatic landing in CAT3 conditions flight scenario.

4.1. WDA for automatic landing

In the case of automatic landing, the functional purpose is 'landing the aircraft in CAT3 conditions' (Figure 3). Values and priorities alongside which the achievement of this purpose is measured are the same as for manual landing scenario.

The physical objects level includes all the objects involved in this phase of flight, irrespective of whether they are internal to the aircraft or external. Each of these objects provides a set of affordances which are depicted at the object-related processes level. For example, the FLARE mode provides two affordances: it indicates the auto land capability of the aircraft and it automatically flares the airplane. Similarly, the runway provides both a location for landing and sufficient space for landing.
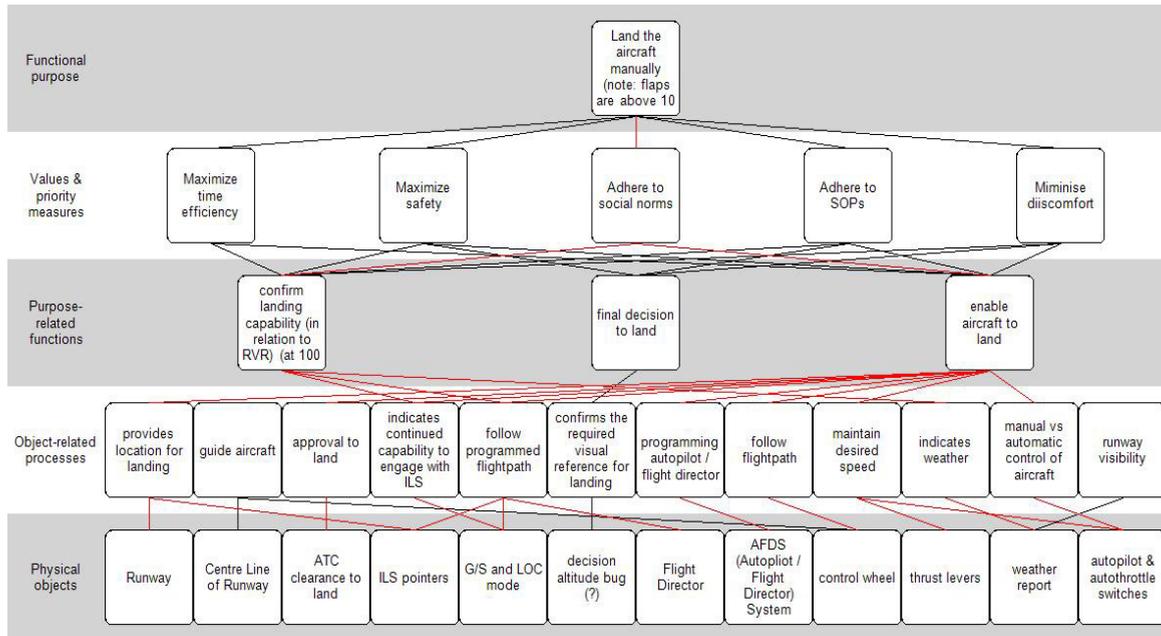
Fig. 3. Abstraction Hierarchy for Automatic Landing.

The purpose-related functions level groups the affordances on the object-related purposes level into the following functions: confirm capability for landing, monitor landing capability, final decision to land, enable aircraft to auto land. Confirming capability for landing implies confirming the status of the systems required for auto landing, runway visibility, continuous indication of capability to engage with ILS, display capability to follow the centre line on the ground, automatically follow the programmed flight path, indicators of the auto land capability of the aircraft. Monitoring landing capability implies obtaining approval to land, confirming runway visibility, continuously monitoring the indication of capacity to engage with ILS, monitoring the capability to follow the centre line on the ground, monitoring the process of automatically following the programmed flight path, monitoring the indicators of auto land capability of the aircraft. The final decision to land depends on the conformation of the required visual reference for landing. Enabling the aircraft to auto land implies the existence of a location for landing, the existence of sufficient space for landing, confirming the indication of capability to engage with ILS, conforming the capability to follow the centre line on the ground, automatically following the programmed flight path, automatically closing the thrust levers, automatically flaring the aircraft, programming the autopilot and flight director.

4.2. CAT and SOCA-CAT for automatic landing

The CAT (Figure 2) maps the functions identified during the WDA to the temporal situations that define the landing phase. Chronologically, these temporal situations are: prior to top of descent (cruise altitude), approach ban (1000R), prior to 200R, decision height point, just prior to touchdown (1-5 seconds before touch down), and touchdown. Automatic landing requires a close collaboration between pilots. Briefings on aircraft status and the close monitoring of aircraft systems is currently performed in collaboration between the Pilot Flying and Pilot Non Flying. When designing for distributed crewing operations, cross-checking roles need to be accounted for both in functional terms and in terms of social dynamics.

5. Initial design recommendations based on the CWAs

Manual landing requires strong flying skills and efficient interaction between the pilots and the flight deck systems. In addition to this, automatic landing requires the effective monitoring of the flight deck systems and quick reaction time for fault alerts. This translates into different system design requirements in a distributed crewing

context – manual landing calls for designing for jointly controlling the aircraft with potential novel human roles in the system, whereas automatic landing calls for distributed situational awareness.

6. Towards mixed-method integration

As outlined in the introduction, multiple research groups investigate SPO simultaneously (e.g. NASA [2], the UK based Future Flight Deck consortium and the EU funded ACROSS (Advanced Cockpit for Reduction Of StreSs and workload) consortium using heterogeneous methodologies. Using multiple methods is not simply the consequence of research activities being distributed. Aviation is a complex system in the sense that closely interacting heterogeneous (human and non-human) actors distributed in space and time bring forth aviation performance. Hence, heterogeneous methodologies are required to investigate aviation performance in a holistic way. Types of information that potentially need to be integrated include expert interviews, task analyses, experimental studies (cf. [2]) as well as historical analysis of aviation practices, regulation analysis [4] and accident investigations [11]. The lack of tools to support mixed-methods integration acts itself as a constraint on progressing towards SPO.

Our current work include investigating SPO pilot performance and task distribution between the flight deck and ground stations with CWA (a semi-structured task analysis) and experimental studies. However, we are aiming to develop considerations for mixed-methods integration that point beyond our project to facilitate potential collaboration between remote research groups. In the next paragraphs challenges associated with mixed-methods integration will be outlined followed by initial recommendations for overcoming them in the context of SPO design.

Mixed-method integration poses epistemological and methodological challenges. Mixed-methods integration can be desired in the context of a single study [12], or across studies that in some form relate to the studied phenomenon [13]. From an epistemological point of view, the relationship of the information obtained with various methods and their relationship to the object of the study needs to be established. [13] lists five approaches to strategically grounded mixed-methods research and labels them according to the 'logics' that guide each strategy. The five logics are the 'rhetorical logic', 'parallel logic', 'integrative logic', 'corroborative logic', 'multi-dimensional logic'. The goal of the rhetorical logic is to add depth or breadth to research and to embellish the result obtained with any methodology. This can be obtained with loose integration. Parallel logic consists of designing studies using different methodologies as partially independent sub-projects under the umbrella of a topic broadly conceived. Under the integrative logic, studies using different methodologies can be conceived as components that shed light on different aspects of a holistic research question, similar to pieces in a jigsaw or layers of a cake. The corroborative logic consists of 'measuring' a phenomenon "from two or more different vantage points, in order to pinpoint the phenomenon, or to improve, test or validate the accuracy of the observation" (p. 8.). Finally, the multi-dimensional logic assumes that the phenomenon we seek to explain is inherently multidimensional and that dimensions "exist in an uneasy or messy tension, rather than being neatly integrated within one plane or dimension (like the wedding cake or the jigsaw puzzle)". On this account, different methods have distinctive strengths and potential which, if allowed to flourish, can shed light on aspects of the phenomenon that coexist. On this account, "the different ways of perceiving and interrogating the social world represented in different methods are themselves part of that multidimensionality" (p. 9.) Instead of aiming for an "integrated account or explanation" (p. 10.) such as under the integrative logic, or "a series of parallel accounts" (p. 10.) such as under the parallel logic, multi-modal explanations "which are based on the dynamic relation of more than one way of seeing and researching" (p.10.). The logic that best reflects mixed-method integration in the context of designing SPO is to be determined as research efforts progress. Upon first reflection, it seems likely that not one but multiple logics may reflect the challenges posed by SPO design depending on sub-research questions. Designing SPO can be understood as an umbrella term that encompasses multiple sub-research questions, e.g. identifying optimal task allocation between actors in the system, designing interfaces in cockpits and ground stations that enable safe operational performance, determining safety levels of alternative system architectures, identifying stakeholders that would need to be taken on board if the SPO concept was to be introduced including professionals working in the aviation system and the public whose perception has a deciding role in the success of business innovation. Depending on the sub-question that one focuses on, the most suitable strategy for mixed-methods integration may vary. Some aspects of SPO design such as identifying optimal task allocation between flight deck and ground crew may require a mixed-method integration

strategy most similar to the 'corroborative logic'. Here, alternative designs for task allocation need to be studied with multiple methodologies including task analysis and experimental design in order to arrive to robust results. Other aspects such as tracing changes in communication with ATC and ground personnel alongside with the optimal function allocation between flight desk and ground crew requires inferring optimal task distribution system-wide in a holistic (cf. [7]) way which may require a strategy most similar to the 'integrative logic'. Finally, determining the future of SPO in a way that integrates human factors studies assessing function allocation with the opinion dynamics and media communications that affect customer choice may require an approach to mixed-method integration that is most similar to the 'multi-dimensional logic'. Pilot interests, airline interests and public opinion [cf. 14] and their effect (both 'explicit' and 'implicit') on aviation performance are part the inherent multidimensionality of the aviation industry. From a methodological point of view, mixed-method integration requires solutions that guide linking the various types of information in a way that conclusions can be drawn based on jointly considering them. The data visualization and manipulation enabled by digital platforms facilitate mixed-method integration [15]. In particular, labels can be identified to link various data types [12], which, similar to a hypertext this enables drawing on multiple sources in one argument. If mixed-method integration is required in one single study, labels can reflect the relationship between data types such as in [12]. Alternatively, if mixed-methods integration is required across sub-studies such as in the case of SPO design, labels might reflect the relationship of pieces of information (results) to characteristics of the phenomenon that is to be inferred. The exact nature of labels may change according to the strategy of mixed-method integration outlined above. In our current work data labels reflect functional units of analysis in the aviation system identified with the help of the CWAs.

Acknowledgements

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