Work domain analysis for assessing simulated worlds for ATC studies

T. Xiao, P. M. Sanderson, M. Mooij, & S. Fothergill
The University of Queensland, Brisbane, Australia

Work Domain Analysis (WDA) was used in a study of the workload of en route Air Traffic Controllers (ATCos) to help characterise the fit between different ATC simulated worlds and our research aims. A WDA captured the ATCo's reasoning space in a way that exposed potential sources of workload, and it was then applied to three cases. Case 1 was the use of a simple laboratory program originally developed to study basic cognitive processes relating to conflict detection and separation. The program captured simple work domain properties relating to safety only. Case 2 was the use of an interactive ATC microworld to study ATCos' separation strategies and workload. The microworld captured a broader range of work domain properties related to safety and expeditiousness. Case 3 involved the evaluation of a task load metric in a full-scale ATC simulator operated by our industry partner, Airservices Australia. The simulator captured the broadest range of work domain properties related to safety, expeditiousness, and orderliness. Overall, WDA can be a useful tool for (a) helping research teams determine the appropriate level of work domain fidelity to examine specific research questions and (b) communicating the strengths and weaknesses of different simulated worlds for the purpose of research.

INTRODUCTION

When researchers use simulated worlds to examine human performance in complex systems, it is important that the simulated world offers a level of fidelity that is consistent with the research question and the phenomenon of interest. Researchers need to determine the minimally adequate level of fidelity required in a simulation to explore a specific research question (Gray, 2002; Hilliard, 2007; Naikar & Sanderson, 1999; Rasmussen, Pejtersen & Goodstein, 1994; Woods & Christoffersen, 2002)

We were faced with the problem of determining appropriate levels of fidelity for experimental settings in a major research project whose objective was to model the mental workload of en route air traffic controllers (ATCos). This paper shows how we used Work Domain Analysis, a modelling approach from the Cognitive Work Analysis framework, to communicate what properties of the ATC work domain were and were not being captured by different ATC simulated worlds.

Air Traffic Control Management Modelling Case

The objective of the project was to “develop a computational model that could simulate how air traffic controllers perform key components of their job and the consequences of their performance for the safety and effectiveness of the air sector that they are controlling” (Neal, 2007). A key goal was to develop a model of mental workload that ATCos experience in en route radar sectors.

During the project, we had access to a variety of test environments ranging from simple laboratory-based conflict detection tasks to high-fidelity in-the-field training simulators. The presence of these options stimulated questions about what properties of the ATC domain could and could not be captured by the different test environments, and which environment to use for which questions. We had to judge how well each environment might help us achieve our research goals, and to determine what further tools or tool development was needed.

Cognitive Work Analysis and Work Domain Analysis

Cognitive Work Analysis (CWA) is concerned with identifying physical and intentional constraints that shape possible activity in a work domain, rather than specifying activity itself. Therefore, CWA is particularly suited for modelling complex adaptive systems, such as air traffic control, in which work practices need to be adaptable given changes and disturbances in the work environment.

Work Domain Analysis (WDA) is the first phase of CWA. A WDA uses a means-ends structure to show how the physical aspects of a work domain are combined to serve the functions and purposes of the work domain. The resulting WDA shows the “functional structure” of the work domain and identifies the reasoning space that is available, in principle, to workers not only as they do normal work but also as they reason adaptively to solve challenging and unfamiliar work problems (Rasmussen et al., 1994; Vicente, 1999).

Although CWA has mainly been used for display design (Lintern, 2006; Vicente, 1999; Watson & Sanderson, 2007), it is equally useful for other purposes (Lintern & Naikar, 2000; Naikar, Pearce, Drumm & Sanderson, 2003; Naikar & Sanderson, 2001; Xu, 2007). Importantly for our purposes, CWA has also been used to describe the match and mismatch between experimental settings and participants (Rasmussen et al., 1994) and to specify simulator requirements and training needs (Hilliard, 2007; Naikar & Sanderson, 1999). WDA is uniquely suited to this task because the format in which the functional structure of the work domain is captured makes it easy for the researcher to determine what should and should not be included in a simulation, given the research focus.

For our ATC analysis we used WDA to help us assess the representativeness of experimental settings and the appropriateness of such settings for given research questions within a research program. First, WDA represents both the intentional and physical constraints that the worker experiences in the work domain. Therefore, we can assess physical and psychological fidelity issues. Second, WDA reveals relationships between constraints across different levels of abstraction. For example, we can track what types of physical affordances are needed to perform certain functions. Therefore, a researcher can identify whether they have provided materials and resources that are relevant to the particular function they are investigating. Third, WDA provides an event-independent representation of the work domain. Therefore, judgments about fidelity are not limited to a specific task or activity, allowing more robust assessments.

To communicate these ideas with the rest of our research group, who were unfamiliar with CWA and WDA, we constructed a simple high level aggregated WDA of the air traffic control domain (Sanderson & Mooij, 2004). Once we had completed the WDA, we were able to overlay the representations of the work domain that each test environment provided. By doing this, we made explicit the work domain properties that were and were not represented. This stimulated discussions on the adequacy of our empirical representations and tools for the purposes of our studies.

WDA of en route ATC

Description of WDA. Our simplified WDA modelled en route air traffic control from the point of view of the ATCo (rather than of pilots or schedulers) (Sanderson & Mooij, 2004). The resulting WDA is shown in Figure 1. For clarity in communicating to fellow researchers, the five WDA levels were given slightly different labels from those usually used.

For the Domain Priorities level (elsewhere termed Abstract Function or Priorities/Values), we adopted the three key priorities of ATC as embodied in the Airservices Australia mission: *safety* in the sense of remoteness from collision, the *orderliness* of traffic through the airspace in terms of the familiarity and tractability for management of the air picture, and the *expeditiousness* or dispatch with which aircraft are moved through the airspace so as to reduce travel time and costs.

For the Domain Functions (elsewhere referred to as Generalised Function or Purpose-Related Functions), we identified functions associated with conforming to legislated *separation assurance standards*, the existence of conventional *profiles and patterns* of traffic management, the management of and negotiation between airspace *jurisdications*, and functions associated with controlling aircraft, which involve appropriate *timing and energy use*.

The Physical Objects and their Physical Functions identified in the bottom two layers of the WDA were restricted to *weather* and the constraints it imposes on airspace, *aircraft* and specific paths they take in space, *sectors* with their lateral and vertical boundaries, and air *routes* with their specified locations, directions, and relationships.

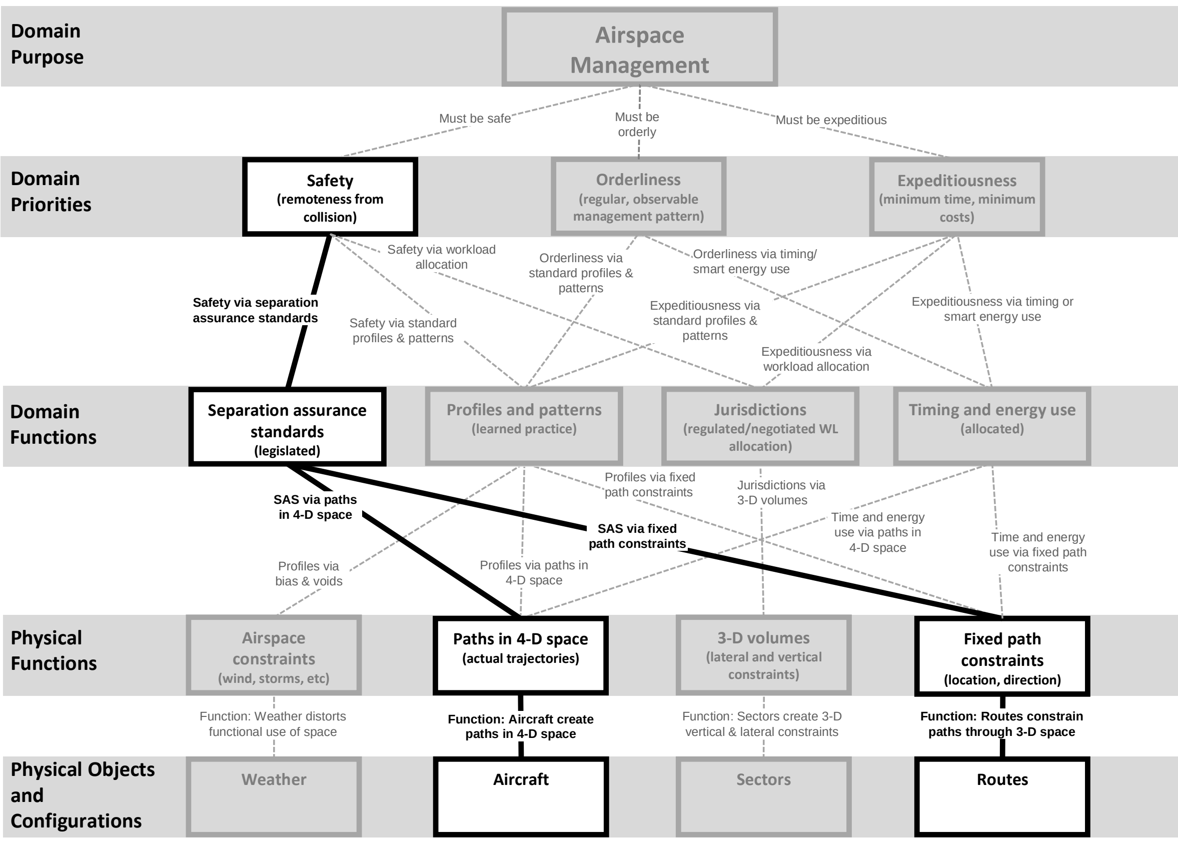

Figure 1. Work domain analysis of en route ATC from the ATCo's point of view. Case 1: Conflict detection and separation. Unshaded and bolded nodes indicate objects, functions and priorities that this study captures.

Comparison with other ATC WDAs. Given perennial concerns about the reliability of WDA, it is interesting to compare the Sanderson and Mooij (2004) WDA of en route ATC with two WDAs of ATC performed subsequently and independently of it by Ahlstrom (2005) and by Kilgore, St-Cyr, and Jamieson (in press). Differences are expected between the three models because they were developed for different purposes, but there are nonetheless striking similarities, especially at the upper levels. The Alhstrom (2005) WDA was motivated by the desire to build better ATC weather displays for the terminal area rather than to study workload in en route control. The top two levels of Ahlstrom's WDA are very similar to ours, but without orderliness as a Domain Priority. At the lower three levels Ahlstrom's functions relate to the functions of information systems and displays rather than of airspace itself—a different focus.

The Kilgore et al. (in press) WDA is based on the TRACON ATC microworld. The analysis was motivated by the pedagogical goal of showing how a moderately complex work domain could be analysed with all five phases of CWA. The Kilgore et al. ATC WDA places route planes safely and route planes efficiently at the top Functional Purpose level which is similar to Sanderson and Mooij's (2004) Domain Purpose of airspace management. At the Domain Priorities level, where Sanderson and Mooij used safety, orderliness and expeditiousness, Kilgore et al. use functions that touch on the former concepts but add to them: aircraft responsibility, pilot situation awareness, field of safe travel, aircraft performance characteristics, passenger comfort, and scheduling demands. At the Domain Functions level there are tighter similarities, with Kilgore et al. specifying coordination with ATCos in neighbouring regions (our jurisdiction functions), establishing and modifying flight plans, aircraft locomotion (our profiles and patterns plus our allocated timing and energy use), and transitioning between airspace (again, our jurisdictions). Overall, though, it is likely that our WDA and the Kilgore et al. WDA would have led to similar conclusions about the test environments.

CASE STUDIES

In the following sections, we discuss how we used WDA to examine what the three different test environments could and could not capture.

Case One: Conflict detection and separation

Before the project began, we had access to an existing test environment: the air traffic control laboratory simulator (ATC-lab; Loft, Hill, Neal, Humphreys, & Yeo, 2004). In this program, conflict detection and resolution situations were originally used as a means of studying memory and cognition issues, such as negative transfer (Loft, Humphreys & Neal, 2004). Non-ATCo participants were presented with multiple short dynamic scenarios and were required to (a) detect and indicate pairs of conflicting aircraft and/or (b) resolve conflicts by changing aircraft speeds. A lateral separation standard of 5 km was used. However, the test environment did not represent altitude and the only interactive element was a basic aircraft speed control.

In order to study conflict detection and resolution in a way that would inform models of ATCo workload, a new laboratory simulator was developed. Altitude was added, and resources familiar to ATCos were added, such as velocity vectors, history dots, and range and bearing lines. As in the previous case, the simulator presented participants with discrete conflict problems to solve rather than continuous traffic scenarios to manage. Using this test environment, the researchers examined the likelihood of whether and when ATCo participants reported they would intervene, given different conflict geometries (Neal, 2007).

In the above studies, only the Domain Priority of safety and the Physical Objects of aircraft and routes were captured along with their functions (see Figure 1). The focus on conflict detection and resolution posed a problem given our research interests because it only partly captured the Domain Function of separation assurance, which is the broader process of keeping planes apart. ATCos usually act to prevent aircraft from reaching situations where they are in conflict and conflict detection in itself is not a function of the work domain. Sources of workload related to achieving expeditiousness and orderliness were also not represented.

We needed to capture changes in the behavioural responses of ATCos due to different workload demands. ATC-lab and its derivatives could only be used to investigate the relationship between aircraft configurations and ATCo assessments of conflict risk. For the next case, ATC-lab was modified so it could not only adequately capture the separation assurance function but also properties contributing to expeditiousness.

Case Two: Separation strategies and workload

The aim of this study was to examine the effect of workload on conflict resolution strategies and the efficiency of these strategies for aircraft (Fothergill, in preparation). One of the authors presented licensed en route ATCos with 12 five-minute scenarios using ATC-Lab^{Advanced} (Fothergill, Loft, & Neal, 2007). The ATCos were instructed to scan, monitor and resolve any potential conflicts within a fictitious generic airspace. The researcher developed the scenarios with guidance from a subject matter expert.

Figure 2 shows the WDA functions that ATC-Lab^{Advanced} captured. The ATCos could manage the airspace in real time and perform activities that would prevent conflicts from occurring, thereby more fully capturing the Domain Function separation assurance. Traffic load was manipulated to test how ATCos trade off between efficiency and safety as workload increases. Therefore, this test environment captured the Domain Priority of expeditiousness and the Domain Function of timing and energy use, in addition to the properties that the previous study captured. Furthermore, ATCos were required to coordinate with imagined ATCos in neighbouring sectors. Therefore, they needed to maintain some level of awareness of jurisdictions and sector constraints. The experimenter provided a handover briefing at the start of each scenario that included information about incoming weather and traffic, allowing ATCos to use general even if not specific professional knowledge about profiles and patterns.

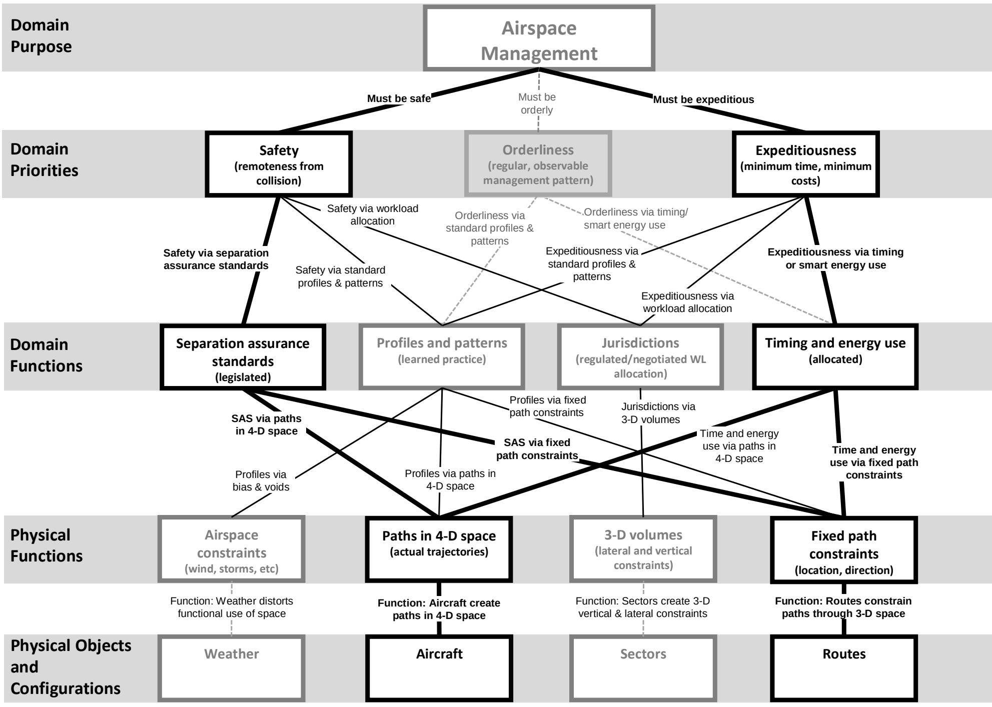

Figure 2: Case 2: Separation strategies and workload. Unshaded nodes indicate objects, functions and priorities that this study captured. Black border and text indicates good representation of the function; grey border and text indicates partial or weaker representation.

A limitation of this study with respect to exploring sources of ATCo workload was that the short scenarios combined with the strong emphasis on safety and expeditiousness may have downplayed reasoning associated with orderliness. Nonetheless, the updated ATC-Lab environment does seem to have captured all the important properties of the work domain relevant to the research question. For the next case, we move to a high fidelity simulator where we were able to capture properties related to safety, expeditiousness, and orderliness.

Case Three: Evaluation of a task load metric

The aim of this study was to assess the ability of a task load metric (method of measuring load experienced by a worker) developed by professional ATCos to predict ATCo workload for routine and non-routine scenario events. We also examined the generalizability of the task load metric across different sectors (Sanderson, Mooij, & Neal, 2007).

The test environment was a high fidelity training simulator. The scenarios were developed in close consultation with subject matter experts from the relevant sectors. Eighteen licensed ATCos performed the experiment on the sector they regularly worked in the operational environment. We presented ATCos with three 30-minute scenarios and asked them to control the traffic as they normally would. During the scenario, the ATCo interacted with 'pilots' and 'other ATCos' played by ATC trainers working in the simulator suite.

Given the broader focus of this study, it was important that the test environment capture all the properties of the work domain (see Figure 3). Familiar sectors were used and subject matter experts familiar with the sectors scripted the scenarios. Hence, ATCos were constrained by their knowledge of the profiles and patterns of the sectors. Each scenario was played out over a longer timeframe (30 minutes) compared to the previous test environment (5 minutes). Therefore, ATCos had more opportunities to reason about the Domain Priority of orderliness. The ATCos could communicate with other agents (e.g. pilots, ATCos) instead of imagining their utterances as in the previous study. Thus, jurisdiction and sector constraints played a more prominent role in this test environment. The scenarios involved separation assurance and timing and energy use constraints that would have forced ATCos to consider tradeoffs between safety, orderliness and expeditiousness. The simulator also represented all physical constraints relevant to all the higher-order domain functions.

CONCLUSION

WDA provides a powerful tool for identifying work domain properties that are needed in a test environment given a certain research question (Hilliard, 2007; Rasmussen et al., 1994). WDA not only represents the functional and physical constraints of the work domain, but also shows how they are related. By examining the constraints that are active, researchers can determine whether their research question can be answered effectively. Such an approach has important implications for simulator design (Hilliard, 2007).

WDA also helps prevent overgeneralization of research findings because it makes explicit which properties of the work domain each test environment does and does not address (Rasmussen et al., 1994). Finally, WDA can be used to guide discussion among researchers and domain experts about how the properties of a work domain can be handled by a set of experiments to serve the purposes of a particular research aim.

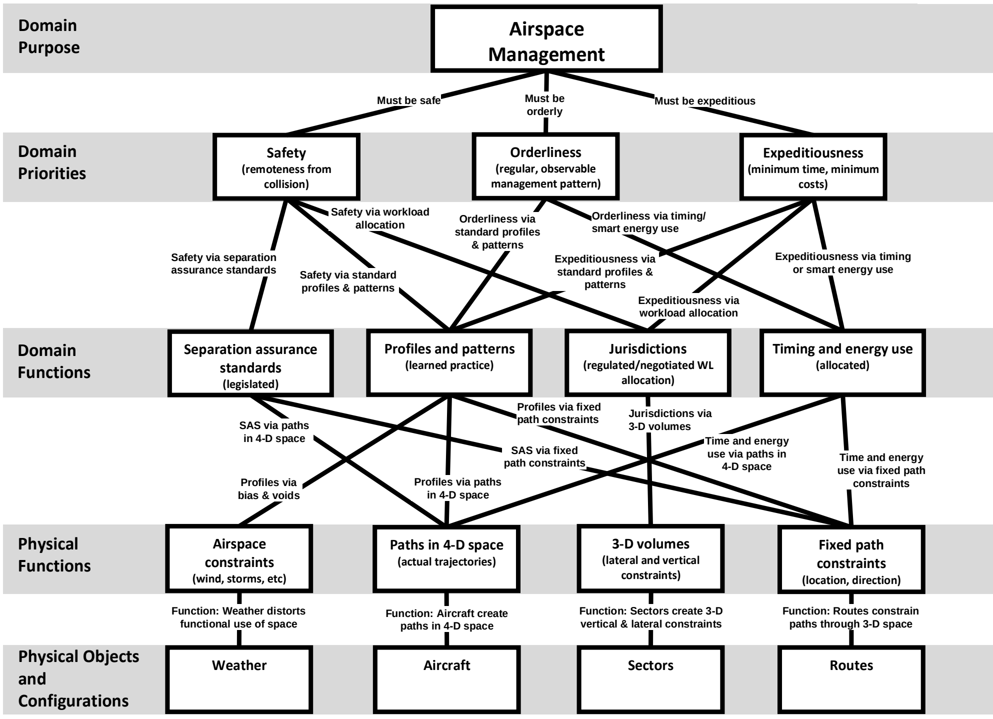

Figure 3: Case 3: Evaluation of the task load metric tool in a full-scale ATC simulator.

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