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Analysing activity in complex systems with cognitive work analysis: concepts, guidelines and case study for control task analysis

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Cognitive work analysis is gaining momentum as an approach for the analysis, design and evaluation of complex sociotechnical systems. This paper focuses on control task analysis (ConTA), the second phase of cognitive work analysis. The paper consolidates existing approaches to ConTA and extends the basic concepts, in particular, by asserting that activity in some work systems is better characterized by both work situations and work functions and by introducing a new formative representation for ConTA called the contextual activity template. In addition, the paper proposes a set of methodological guidelines for performing ConTA and presents a case study of a ConTA for a first-of-a-kind military system called Airborne Early Warning and Control. As well as illustrating the conceptual extensions and methodological guidelines for ConTA by example, this case study highlights some of the difficulties of conducting ConTA for first-of-a-kind, complex systems during the early stages of development.

Keywords: Cognitive work analysis; Control task analysis; Decision ladder; Step ladder; Cognitive task analysis; Task analysis; System development

1. Introduction

Cognitive work analysis (Rasmussen *et al*. 1994, Vicente 1999) is gaining momentum as an approach for the analysis, design and evaluation of complex sociotechnical systems. Cognitive work analysis (CWA) has been used for: designing interfaces (Vicente 1992, Vicente *et al*. 1995, Rasmussen 1998, Reising and Sanderson 1998, Dinadis and Vicente 1999, Burns 2000, Burns *et al*. 2000, Linegang and Lintern 2003); developing decision support systems (Gualtieri *et al*. 2001); designing teams (Gualtieri *et al*. 2000, Naikar *et al*. 2003); evaluating design proposals (Naikar and Sanderson 2001); analysing training needs (Naikar and Sanderson 1999, Naikar and Saunders 2003); and developing specifications (Leveson 2000). Most of these studies were based on work domain analysis, the first phase of CWA.

Relatively little attention has been given to control task analysis (ConTA), the second phase of CWA. The most comprehensive accounts of ConTA are provided by Rasmussen *et al*. (1994), Vicente and Pawlak (1994) and Vicente (1999).

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However, Rasmussen and Vicente present somewhat different approaches to ConTA. Moreover, they focus on theoretical concepts with only a comparatively limited discussion of a methodology for ConTA. Other studies that involve ConTA only focus on some of the elements of ConTA and they provide very little insight into how the analyses were performed (Roth and Mumaw 1995, Roth *et al*. 1993, Benda and Sanderson 1999, Potter *et al*. 2000, Sanderson and Naikar 2000, Hori *et al*. 2001, Bisantz *et al*. 2003, Naikar and Pearce 2003, Naikar and Saunders 2003, Naikar *et al*. 2003). The application of ConTA is, therefore, limited by the lack of a coherent set of theoretical concepts and methodological guidelines.

For the analysis of complex, military systems, it has been necessary to consolidate the different approaches to ConTA (Rasmussen *et al*. 1994, Vicente 1999) and to develop methodological guidelines for ConTA. Furthermore, it has been necessary to extend the basic concepts for ConTA. Many of the military systems had characteristics that were dissimilar to the process control and electronic troubleshooting domains in which the concepts for ConTA were originally developed. Table 1 summarizes some of the main characteristics of the domains that have been the basis of previous ConTA (Rasmussen *et al*. 1994, Vicente 1999) and the military domains that were studied (Naikar and Pearce 2003, Naikar and Saunders 2003, Naikar *et al*. 2003). The characteristics that are listed for each domain are not necessarily relevant to all of the studies conducted in those domains. For example, the analysis of DURESS, a process control micro-world simulation, was conducted before a real-time simulation existed (Vicente 1999) and some of the military systems that were studied were existing, functioning systems (Naikar and Saunders 2003). The main point is that the conceptual extensions and methodological guidelines that were developed for ConTA may be relevant for analysing other kinds of systems with similar characteristics to the military domain.

The aim of this paper then is to contribute towards developing a coherent approach to ConTA by: consolidating the approaches of Rasmussen and Vicente to ConTA; describing the conceptual extensions and methodological guidelines that were developed for ConTA; and presenting a case study of a ConTA for a first-of-a-kind military system. Unless it is necessary for coherence, the work in earlier texts (Rasmussen *et al*. 1994, Vicente and Pawlak 1994, Vicente 1999) is not duplicated. The intention is to complement what has previously been written about ConTA.

2. Cognitive work analysis

CWA may be contrasted with normative and descriptive approaches to work or task analysis (Vicente 1999). Normative techniques focus on prescribing how work *should* be done. Many of the traditional approaches to task analysis, particularly those which focus on physical, observable behaviours, may be placed in this category (e.g. Taylor 1911, Miller 1953, Card *et al*. 1983, Kirwan and Ainsworth 1992). These techniques are best suited to highly stable and proceduralized work systems, like assembly line operations, for which it is possible to anticipate the conditions of work and, therefore, to pre-identify ideal task sequences and timelines for dealing with those conditions. By providing detailed guidance to workers about the ideal way(s) to perform tasks, normative techniques can optimise operators' workload and minimize human error.

Table 1. Some of the differences between the process control and electronic troubleshooting domains that were the basis of control task analysis and the military domains that were studied.

	Process control/electronic troubleshooting domains	Military domains
Nature of constraints	High degree of causal constraints, i.e. the laws of nature.	High degree of intentional constraints, i.e. actors' intentions, values, rules and practices.
Stage in the system life cycle	Existing, functioning systems: detailed information about workers' behaviour and physical artefacts is available.	First-of-a-kind systems at the concept stage of development: detailed information about workers' behaviour and physical artefacts is unavailable.
Size of the problem space	Small problems spaces: can be managed by a single operator, for example, DURESS (Vicente 1999) and electronic troubleshooting (Rasmussen *et al*. 1994).	Large problem spaces: requires multiple operators.
Analysts' access to the work domain	Co-location of analysts with workers is possible: observational techniques can be used for collecting information about the work domain.	Co-location of analysts with workers is impossible: observational techniques cannot be used for collecting information about the work domain, for example, in a two-person strike aircraft.

Descriptive approaches to work analysis seek to understand how work *is* actually done. Many of the techniques for cognitive task analysis, which focus on the cognitive aspects of work, may be placed in this category (e.g. Zsambok and Klein 1994, Seamster *et al.* 1997, Schraagen *et al.* 2000). These techniques were developed in response to technological advances, such as automation, that shifted human work from manual to cognitive tasks. Workers in these systems also have greater discretion for decision-making and problem-solving and, therefore, typically do not—and cannot—rely on normative prescriptions. By understanding the cognitive functions of work and describing how they are actually accomplished in real work settings, cognitive task analysis techniques seek to define how those cognitive functions can be better supported.

CWA, on the other hand, provides a formative approach to work analysis that focuses on how work *can* be done (Rasmussen *et al.* 1994, Vicente 1999). As well as recognizing that many tasks are discretionary and that workers have a great variety of options with respect to what to do and when and how, this approach also recognizes that the main role of human workers in modern, complex sociotechnical systems is to deal with unanticipated events, situations which pose the greatest threat to system safety. Therefore, rather than focusing on how work should be done or how work is done under particular conditions or in particular situations, CWA focuses on the constraints that shape work in the first place. Within these constraints workers can *form* or generate a large variety of work patterns including novel behaviours to deal with unanticipated events—that is why CWA is described as a formative approach to work analysis. By focusing on constraints, rather than on particular ways of working, CWA aims to support workers in adapting their behaviour online and in real time within system constraints to maintain performance and safety in a variety of situations including unanticipated events. As there are several kinds of constraints that can shape workers' behaviour, several dimensions of analysis are necessary.

Table 2 shows that CWA consists of several phases of analysis for identifying the different kinds of constraints on workers' behaviour. The phases of CWA are presented slightly differently by Vicente (1999) and Rasmussen *et al.* (1994). This paper focuses on the phases(s) of CWA for analysing activity in work systems. These phases are shown in italics in table 2.

Vicente and Rasmussen present somewhat different approaches for analysing activity using the CWA framework. For Vicente, the analysis of activity, or ConTA, involves analysing the operating modes and control tasks of a work system. For Rasmussen *et al.*, the analysis of activity is conducted in work domain terms and in decision-making terms. Table 2 shows that in activity analysis in work domain terms, the focus is on identifying work situations and work functions;[1] these are similar to Vicente's operating modes. In activity analysis in decision-making terms, the focus is on identifying decision-making functions; these are the same as Vicente's control tasks. The concept of operating modes is not discussed extensively by Vicente (1999); in fact the discussion is limited to only a few sentences. Rather, Vicente gives prominence to analysing activity as a set of control tasks. In contrast, Rasmussen *et al.* emphasize the analysis of work situations and work functions to the point of presenting it as a distinct sub-stage of activity analysis—activity analysis in work domain terms.

This paper consolidates the approaches of Vicente and Rasmussen to ConTA. It mainly adopts Vicente's terminology because it is the more recent formulation of

Table 2. The phases of CWA as they are presented by Vicente (1999) and Rasmussen *et al*. (1994) and the types of constraints that are the focus of each phase of analysis.

Vicente (1999)	Rasmussen *et al*. (1994)	Types of constraints
Work domain analysis	Work domain analysis	Purposes, priorities and values, general functions and physical resources.
Control task analysis	Activity analysis in work domain terms	Operating modes (Vicente 1999). Work situations or work functions (Rasmussen *et al*. 1994).
	Activity analysis in decision-making terms	Control tasks (Vicente 1999). Decision-making functions (Rasmussen *et al*. 1994).
Strategies analysis	Activity analysis in terms of mental strategies	Strategies for making decisions or achieving control tasks.
Social organization and co-operation analysis	Analysis of the work organization	Distribution of work including allocation of work to individuals; organization of individuals into teams; and communication requirements.
Worker competencies analysis	Analysis of system users	Human capabilities and limitations and competencies of workers (e.g. skills, attitudes).

CWA and because it is more commonly used in the latest literature. Therefore, it refers to the analysis of activity using the CWA framework as ConTA and uses the term control tasks instead of decision-making functions. It departs from Vicente's terminology, however, by using work situations and work functions instead of operating modes. It appears that operating modes can be used either for work situations or for work functions, so that for some work systems the operating modes may refer to work situations whereas in other work systems the operating modes may refer to work functions (Vicente 1999). However, as will be shown later in this paper, in some work systems activity can be decomposed into both work situations and work functions. Hence, it is necessary to maintain the distinction between the two. Moreover, in these work systems it can be difficult to decompose activity into control tasks without first decomposing activity into work situations and work functions. The approach presented in this paper, therefore, reinstates the analysis of work situations and work functions as a critical element of the analysis of activity in the CWA framework.

3. Concepts for ConTA

ConTA focuses on *what needs to be done* in a work domain (Vicente 1999). It complements work domain analysis, the first phase of CWA, by identifying the activity that is necessary to achieve the purposes, priorities and values and functions of a work domain with a set of physical resources. ConTA is not concerned with how the activity is carried out or by whom; these aspects are the focus of strategies analysis and social organization and co-operation analysis, respectively. In addition, ConTA is not concerned with the skills and training that are necessary for carrying out the activity; this is the focus of worker competencies analysis.

Traditional approaches to work or task analysis typically decompose activity into sequences of tasks or actions. In the consolidated approach to ConTA that is presented in this paper, activity is first decomposed into a set of recurring work situations to deal with and/or a set of work functions to perform. Activity is then further decomposed into the control tasks that are required for each work situation and/or work function. Whereas Rasmussen *et al*. (1994) decompose activity into either work situations or work functions, this paper discusses a class of work systems where activity is better characterized as a combination of work situations and work functions. This paper also introduces the contextual activity template for modelling activity in these systems. This template highlights the contextual relationships between the various elements of ConTA and graphically illustrates all of the combinations of work situations, work functions and control tasks that are possible.

3.1. *Work situations and work functions*

In most work systems, activity can be decomposed into a set of recurring work situations or work functions. The decomposition of activity into work situations is appropriate in systems where work is segmented according to time and space (Rasmussen *et al*. 1994). To illustrate, activity in hospitals can be decomposed into work situations because many of the activities arise out of a recurring schedule of meetings held in specific locations. So, activity in hospitals can be decomposed into: practitioner's examination, planning for hospitalization, hospitalization, pre-operation and operation. In schools, the activity of teaching staff can be decomposed into work situations such as: class time and recreation time.

In other work systems, activity may not be clearly delimited in time and space. Instead, activity may be better characterized by its content independently of its temporal or spatial characteristics (Rasmussen *et al.* 1994). In these work systems, it is more appropriate to decompose activity into a set of recurring work functions or problems to solve. For example, activity in a library system can be decomposed into work functions such as: cataloguing material and assisting users to retrieve information. In a research laboratory, activity can be decomposed into work functions such as: writing papers, conducting experiments and reading relevant literature.

While Rasmussen *et al.* (1994) suggest decomposing activity into either work situations *or* work functions, in some work systems activity is better characterized as a combination of work situations *and* work functions. These are systems in which activity within a work situation or set of work situations can be further delineated in terms of its functional content. For example, in a military strike aircraft, activity can be decomposed into a set of recurring work situations including: ingress to target, target area and egress from target. Then, activity within a work situation, for example in the target area, can be further decomposed into a set of recurring work functions including: evaluate tactical situation, deliver weapons to target and avoid and escape threats. These work functions may also occur in some of the other work situations but usually not in all of them. Without the further delineation of activity into work functions it can be difficult to analyse the control tasks for each work situation.

Figure 1 shows a contextual activity template,[2] for representing activity in work systems that are characterized by both work situations and work functions. In this template, the work situations are shown along the horizontal axis and the work functions are shown along the vertical axis. The circles indicate the work functions and the boxes around each circle indicate all of the work situations in which a work function *can* occur (as opposed to *must* occur). The bars within each box indicate those work situations in which a work function will *typically* occur. This template, therefore, shows the context, defined by work situations, in which particular work functions can occur.

The contextual activity template also illustrates the various combinations of work situations and work functions that are possible. For example, in Work Situation 2, Work Function A can occur on its own, with Work Function C, with Work Function D or with both Work Functions C and D. In Work Situation 3, Work Function A can also occur in combinations including Work Function B. The work situations and work functions can, therefore, be combined in various ways to form the total response of actors. The various combinations of work situations and work functions will impose qualitatively different sets of cognitive demands on workers.

3.2. *Control tasks*

Further to decomposing activity into work situations and/or work functions, the consolidated approach to ConTA decomposes activity into the set of control tasks for each work situation and/or work function. The decision ladder provides a useful template for identifying control tasks. Figure 2 shows a generic decision ladder with annotations that were developed by reviewing a range of papers by Rasmussen

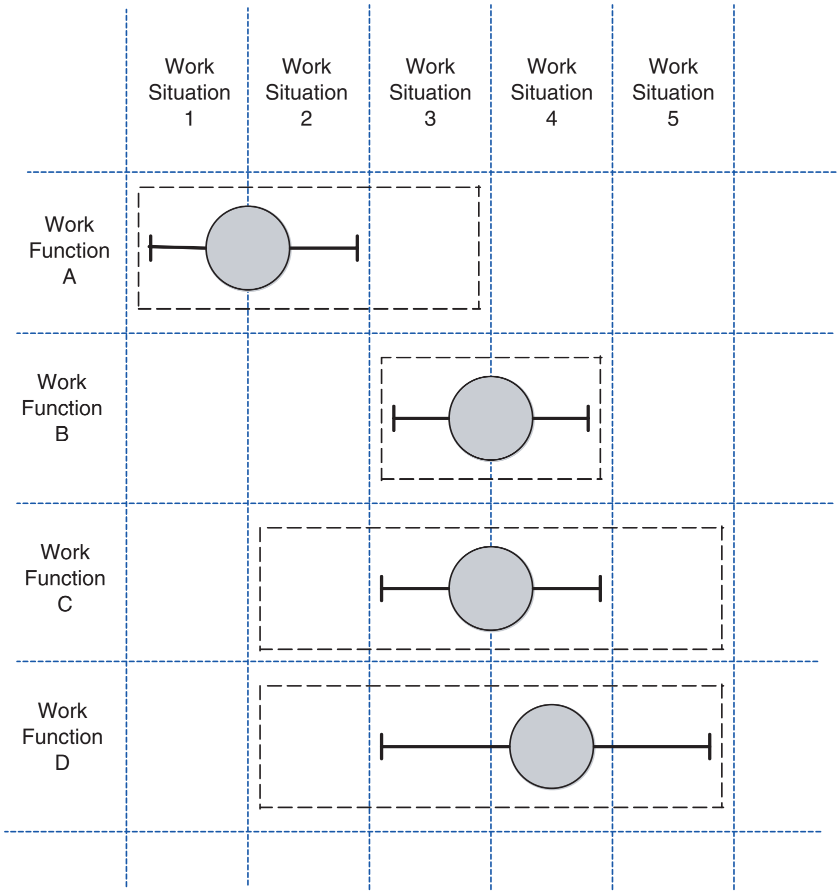

Figure 1. The contextual activity template for representing activity in work systems that are characterized by both work situations and work functions.

and Vicente (e.g. Rasmussen 1976, 1980, Rasmussen *et al.* 1994, Vicente and Pawlak 1994, Vicente 1999).

The decision ladder is comprised of links between boxes and ovals (Vicente 1999). The boxes represent information-processing activities whereas the ovals represent the states of knowledge that are the results or outputs of these activities. So, for example, the information processing activity labelled as *identify state* results in knowledge about the current *system state*. The arrows in the centre of the decision ladder indicate shortcuts from one part of the decision ladder to another. Shunts connect an information-processing activity to a state of knowledge. For example, *observing* information or data in the environment can lead directly to knowledge of the *task* or *procedure* to execute. Leaps connect two states of knowledge indicating that the states of knowledge can be directly associated with one another. For example, knowledge about the current *system state* can lead directly to knowledge about the *task* or *procedure* to execute. Only some examples of shunts and leaps are shown in figure 2. Rasmussen (1976) and Vicente (1999) describe a variety of other shortcuts.

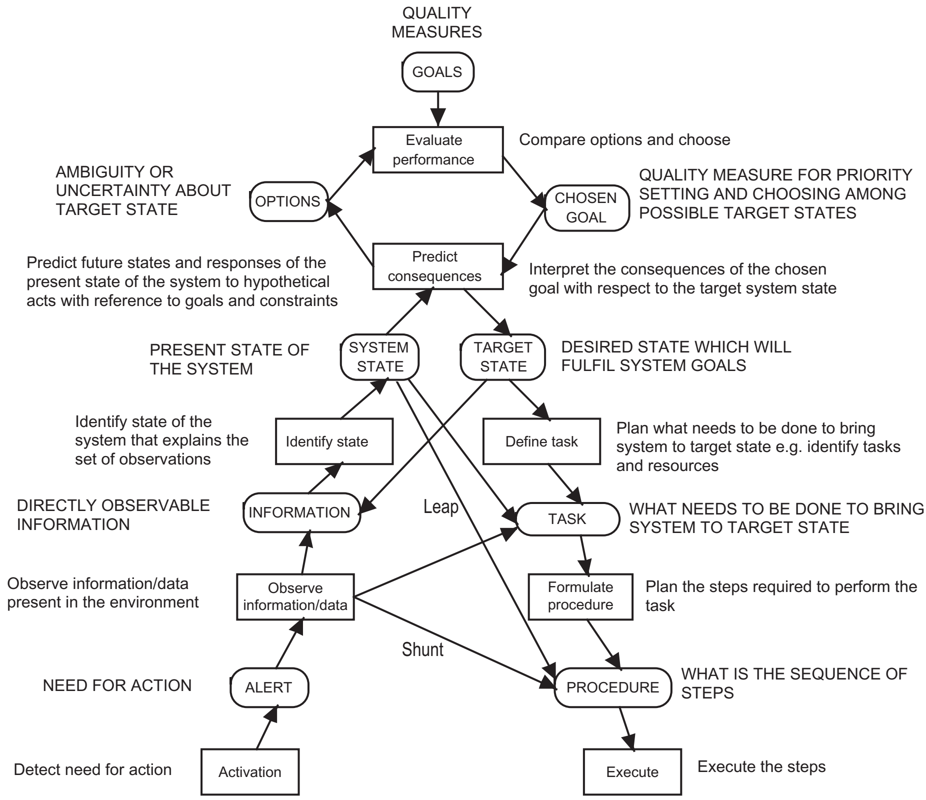

Figure 2. The decision ladder template with annotations that were developed by reviewing a range of papers by Rasmussen and Vicente.

The annotations to the decision ladder reveal that the left side of the template is used for representing control tasks related to identifying the system state. Here, the actual state of the environment or system must be identified through the processes of information gathering and diagnosis. The top part of the decision ladder is used for representing control tasks related to goal evaluation. Here, the implications of the actual state with reference to the current goals must be evaluated in order to determine a target state. This process involves prediction, value judgement and choice. The right side of the decision ladder is used for representing control tasks related to planning and execution. Here, the proper sequence of control actions must be implemented through the processes of identifying tasks and resources and scheduling and carrying out action. Further detail about the different parts of the decision ladder is provided in the next section.

Putting the various properties of the decision ladder together, the left side of the decision ladder is used to represent the control tasks necessary for understanding the current system state, whereas the right side of the decision ladder is used to represent the control tasks necessary for achieving the target system state. On some occasions, observing information or diagnosing the current system state signals the target system state that is desirable or the tasks or procedures to execute; hence, some shortcuts are shown in the centre of the template. On other occasions, understanding the current system state may not signal a target system state or the tasks or procedures to execute. In this case, different options for the target state must be evaluated against the current goals of the system and an option selected that best satisfies the goals of the system; these control tasks are represented at the top of the decision ladder.

The decision ladder departs from traditional models of information processing in several respects (Rasmussen *et al*. 1994, Vicente 1999). First, the decision ladder need not be followed in a linear sequence. Instead, shunts and leaps are possible from one part of the decision ladder to another. Secondly, the decision ladder accommodates various start and end points. That is, activity need not start in the *activation* box of the decision ladder and end in the *execution* box. Instead, activity can begin, for example, with an understanding of the *target state* to be achieved. Thirdly, the flow of activity in the decision ladder need not be in the left-to-right sequence but can occur from right-to-left. The decision ladder, therefore, provides a template for representing the opportunistic form of cognitive activity that Rasmussen (1974) found was the norm in expert behaviour in complex, dynamic environments.

Using the decision ladder, control tasks can be identified in the context of work situations and/or work functions. If activity is decomposed into work situations, control tasks can be identified for each work situation. If activity is decomposed into work functions, control tasks can be identified for each work function. If activity is decomposed into both work situations and work functions, control tasks can be identified for each work function but with different sub-sets of control tasks more likely to be active in different work situations. Figure 3 builds on the contextual activity template in figure 1 by showing a decision ladder for each work function and illustrating that different sub-sets of control tasks are more likely to be active in different work situations. Here, the contextual activity template highlights the context, in terms of work situations and work functions, in which control tasks can occur. The work situations, work functions and control tasks can be combined in various ways to form the total response of actors. The various combinations of work situations, work functions and control tasks will impose qualitatively different sets of cognitive demands on workers.

In summary, the contextual activity template provides a representation for characterizing activity in work systems that can be decomposed into both work situations and work functions. It integrates the various elements of ConTA by highlighting the contextual relationships between work situations, work functions and control tasks. In addition, it provides a formative representation for ConTA by capturing all of the combinations of work situations, work functions and control tasks that are possible. This approach to analysing activity is distinct from traditional approaches to work or task analysis that decompose activity into a relatively small and finite set of tasks or task sequences.

4. Guidelines and case study for ConTA

Having described a set of concepts for ConTA, this paper now presents some methodological guidelines for performing ConTA. To illustrate these concepts and guidelines by example, a case study is also presented of a ConTA for a first-of-a-kind, military system called Airborne Early Warning and Control (AEW&C). Other papers have discussed how this ConTA was applied to develop a team design for AEW&C that has been adopted by the Australian Government (Naikar and Pearce

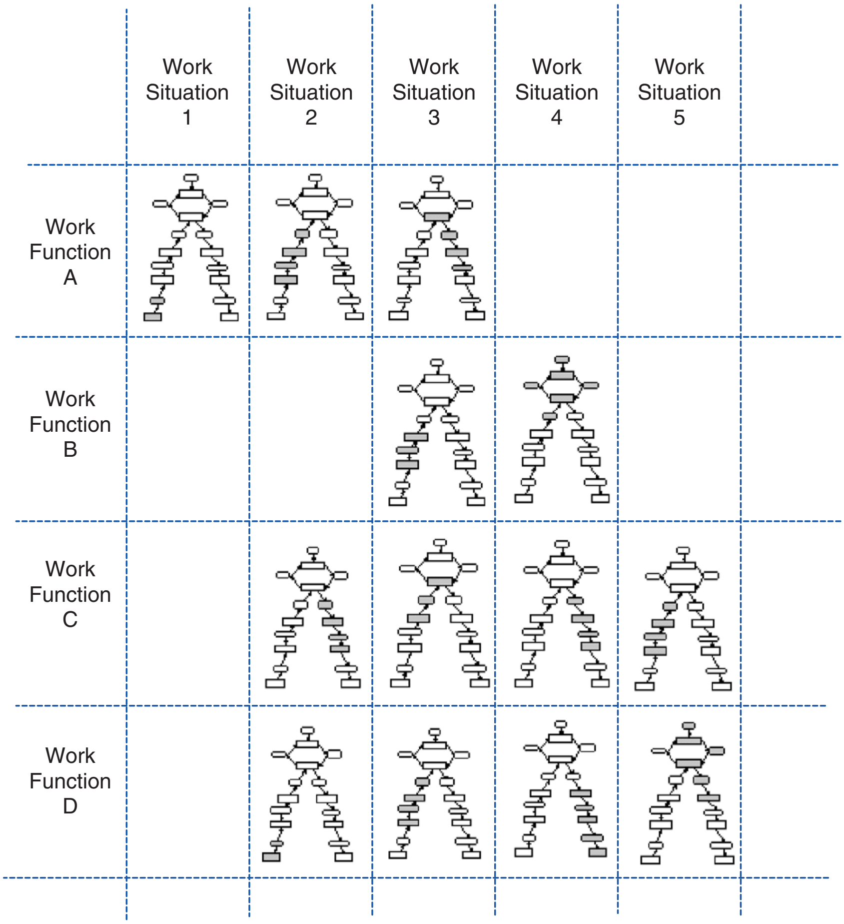

Figure 3. The contextual activity template showing the use of the decision ladder to represent the control tasks for each work function and to illustrate the sub-sets of control tasks that are likely to be active in different work situations.

2003, Naikar *et al.* 2003). This study focuses on the process used to perform the ConTA for AEW&C.

AEW&C is a complex, airborne system that is currently being developed by Boeing for the Australian Government. When it is operational, AEW&C will be crewed by a team of people in the cabin of the aircraft who will be responsible for developing a tactical picture in an allocated area of operations and for co-ordinating the activities of defence assets in that area. This role is similar to that of the Airborne Warning and Control System (AWACS) of the US Air Force and the E2C system of the US Navy. However, AEW&C will have vastly different technology to AWACS and E2C and, therefore, it may be described as a first-of-a-kind system (Naikar *et al.* 2003). The ConTA for AEW&C was conducted prior to and during the initial stages of system development.

Performing a ConTA, following the consolidated approach presented in this paper, consists of two main steps. The first step is to identify *what needs to be done* in a work domain in terms of work situations and/or work functions.

The second step is to identify *what needs to be done* in a work domain in terms of control tasks for each work situation and/or work function. The results of these analyses can then be represented using the contextual activity template. The following sections present a set of methodological guidelines that were developed for performing each of these steps and illustrate how these guidelines were implemented with the AEW&C case study.

4.1. *Analysing work situations and work functions*

4.1.1. Guidelines. The first step of the consolidated approach to ConTA is to identify work situations and/or work functions. To identify work situations and/or work functions, analysts need to examine how work is segmented in the system of interest. Is the work segmented according to a set of situations to participate in, a set of functions to perform or both? If the work is organized into various stages or phases or around the places or areas where it occurs, so that activities are well defined in time or location, the activity should be decomposed into work situations. If the work is organized around particular functions to perform or problems to solve, so that activities are defined by their functional content, the activity should be decomposed into work functions.

It is usually possible to determine how work is segmented in a system from the professional terminology and phrases that are used in the work domain (Rasmussen *et al*. 1994). Often the terminology of the work domain can be used directly as labels for the work situations and work functions; that is why Rasmussen *et al*. (1994) call this level of analysis activity analysis in work domain terms. The professional terminology and phrases of a work domain can be studied using a number of techniques including document analysis, observation of daily work activities, walkthroughs, talkthroughs, interviews and top-down analysis based on work domain analysis (the first phase of CWA). Document analysis and top-down analysis are particularly suitable for systems in the early stages of development, when the systems are not yet functioning, whereas observation of daily work activities, walkthroughs, talkthroughs and interviews are more suitable for established systems.

Irrespective of which of these techniques are used to study the professional terminology and phrases of a work domain, table 3 shows a number of prompts and generic keywords to assist analysts with identifying how work is segmented or organized in a work system. So, for example, irrespective of whether analysts are observing daily work activities or searching through documents, the prompts indicate that analysts should look for evidence for locations in which the work occurs, time periods through which the work progresses or functions that are performed. The generic keywords indicate the different guises in which the organization of work into location, time or function may be revealed in a work domain. For example, workers or documents may refer to place names, stages or phases of work or different roles and responsibilities. Remember, though, that the terminology that is used in a work domain will typically be domain-specific. For example, fighter pilots may talk about flight profiles or weapons delivery profiles. The key is to recognize that these terms refer to various *stages* of flight or weapons delivery, indicating that activity can be decomposed into work situations. The last row in table 3 describes some prompts for examining whether activity in particular work situations is further organized around work functions to perform. The results of this step of ConTA can be used to populate the contextual activity template shown in figure 1.

Table 3. Prompts and generic keywords for identifying work situations and work functions.

	Prompts	Generic keywords
Work situations	Are there different locations in which work occurs? If so, what are all the locations in which work occurs?	Places, meeting locations, positions, sites, stations, locations, spaces, circumstances
	Are there different time periods through which the work progresses? If so, what are all the time periods through which the work progresses?	Stages, schedules, phases, meeting times, states, steps, times, periods, segments, order, sequences, conditions
Work functions	Are there distinctive functions to perform or problems to solve? If so, what are all the functions to perform or problems to solve?	Problems, concerns, assignments, roles, jobs, duties, occupations, responsibilities, tasks, activities, incidents, events, occurrences, cases
Combining work situations and work functions	Do the functions to perform or problems to solve occur in particular locations or time periods? If so, in what locations or time periods can the functions possibly occur? If so, in what locations or time periods do the functions typically occur?	

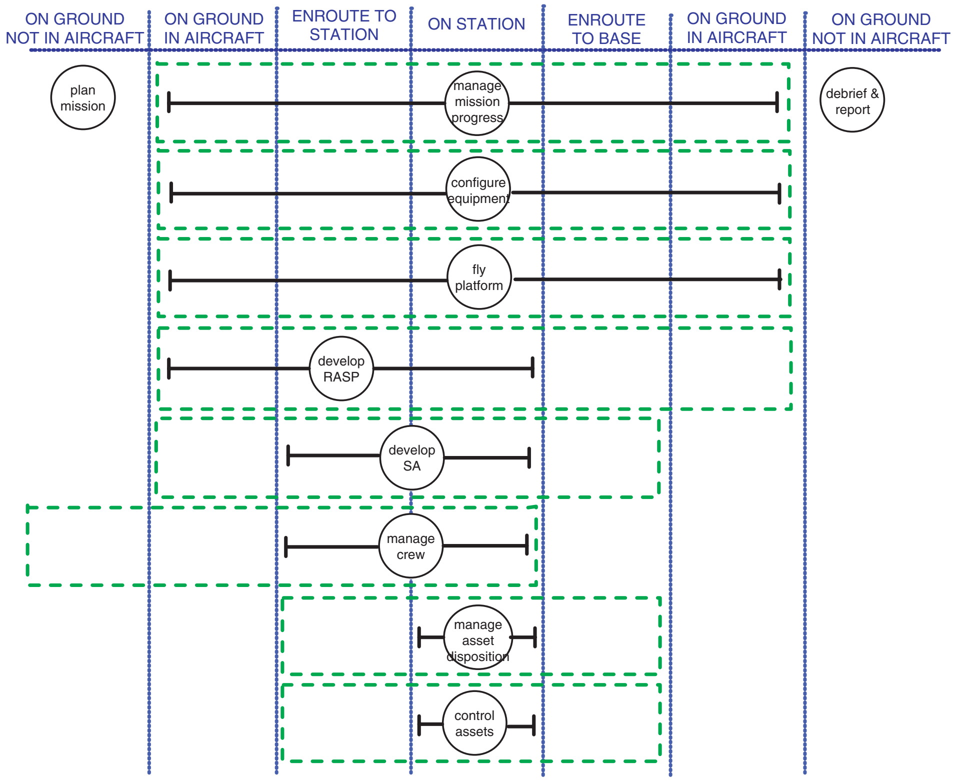

Figure 4. The contextual activity template for AEW&C showing work situations and work functions.

4.1.2. AEW&C case study. Figure 4 shows the contextual activity template for AEW&C. The AEW&C work situations, which are shown along the horizontal axis, are the different phases of a mission. The AEW&C work functions are shown in the circles. The boxes surrounding each work function indicate all of the mission phases in which the work functions can occur. The bars within each box indicate those mission phases in which the work functions typically occur. Extended descriptions of the work functions, which are contained in a supporting document, clarify what each work function involves in terms of the 'problem to solve'. For example, for manage asset disposition the 'problem' is to manage the number, types and disposition (location, weapon status, fuel status, tasking) of assets to achieve the aims of the mission under changing tactical and environmental conditions.

To develop the contextual activity template for AEW&C, the first step was to determine whether AEW&C activity should be decomposed into work situations and/or work functions. To do this, the prompts in table 3 were used to search through existing documents, in particular the AEW&C Concept of Operations, for references to work situations and work functions. The documents contained diagrams of the flight profile or stages of flight for AEW&C which were identified as work situations. In addition, the documents referred to some of the roles of the AEW&C crew and the functions of each role, which were identified as work functions. The documents contained sufficient information to develop a preliminary set of work situations and work functions for AEW&C. Following that, the analysts worked with eight individual subject matter experts to refine this preliminary analysis, that is to review the work situations and work functions; to extend the set of work situations and work functions; and to establish the relationships between the work situations and work functions.

The subject matter experts included three military personnel, two operations analysts and three defence scientists who had been involved in defining the AEW&C system concept. To facilitate discussions with individual subject matter experts, the prompts were modified into questions about the preliminary set of work situations and work functions for AEW&C. For example, with respect to the work situations, the subject matter experts were asked 'are these all the locations in which work can occur', 'are there any other locations in which work can occur' and 'are these all the stages of a flight or mission'. With respect to the work functions, the subject matter experts were asked 'are these all the jobs to perform' and 'are there any other jobs to perform'. The AEW&C work domain analysis was also used to facilitate a top-down discussion about work functions (Naikar *et al*. 2003). Specifically, the analysts explored what 'jobs' or work functions were necessary in light of each of the purposes, priorities and values, general functions and physical resources of AEW&C. Finally, with respect to the combinations of work situations and work functions, the subject matter experts were asked 'in which locations or stages of a mission is it possible for these jobs to occur' and 'in which locations or stages of a mission do these jobs typically occur'.

Identifying the AEW&C work functions required thinking about activity in terms of functions or problems to solve instead of the tasks to execute. However, focusing on tasks was more natural to the analysts and the subject matter experts. For example, with respect to the work function *manage asset disposition*, the tendency was to identify tasks such as monitoring assets, scheduling assets and assigning tasks to assets. This type of information is more relevant to the second step of ConTA which involves identifying control tasks. Therefore, when tasks were identified, it was necessary to examine what the function of the tasks was or the reason for which the tasks were being performed. This process provided the information needed to develop a definition of the work function (see above for a definition of the work function *manage asset disposition*).

The decomposition of activity into work situations and work functions can be done at different levels of detail or granularity. Basically, the decomposition should be continued to a level where it is possible to identify control tasks (Rasmussen *et al*. 1994) and/or to a level that is appropriate for the purpose of the analysis. For AEW&C, it was useful to perform a trial by developing decision ladders for some of the work functions during the early stages of the analysis to check whether the level of granularity of the work functions was appropriate for identifying control tasks and for designing the AEW&C team. The trial confirmed that the level of granularity of the work functions met these requirements.

4.2. *Analysing control tasks*

4.2.1. Guidelines. The second step of the consolidated approach to ConTA is to identify the control tasks for each work situation and/or work function. This section discusses the various parts of the decision ladder template (figure 2). It describes the parts of the decision ladder in terms that are useful to analysts for analysing and recognizing control tasks in complex work domains and provides simple examples for each part of the decision ladder from the domain of military air defence (a comprehensive example of a decision ladder is provided in figure 5). For this discussion, the parts of the decision ladder are labelled in terms of the states of knowledge (e.g. alert, information, system state). Finally, some prompts and generic keywords are described for each part of the decision ladder to help analysts to identify control tasks.

- *Alert*. This part of the decision ladder refers to events or occurrences that can act as alerts to the need for action. For example, in military air defence, *alerts* can be in the form of warning tones or lights or communication from other crew members.
- *Information*. This part of the decision ladder refers to data, facts or information that is available in the environment. The information is in a form that is directly observable or that can be directly picked up from the environment, rather than inferred or calculated. For example, in military air defence, *information* can include the fuel status of assets or the location of threats.
- *System state*. This part of the decision ladder refers to assessments of the current condition, situation or circumstances of the system. The system state is diagnosed from information that is available in the environment. For example, *system state* may include assessments of the amount of time an asset can remain on station given its fuel status or the enemy's intentions. Predictions of the likely consequences of the current system state may lead to a new target state (right side of the decision ladder) or to the identification of options for the target state (top part of the decision ladder).

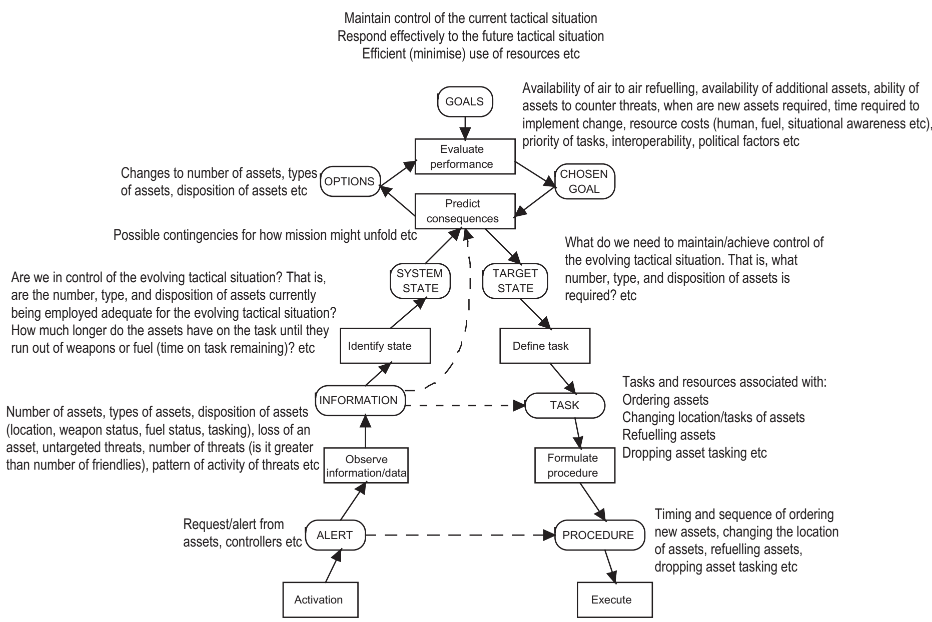

Figure 5. The decision ladder for the AEW&C work function *manage asset disposition*.

- *Options*. This part of the decision ladder refers to choices or alternatives for the target state of the system. *Options*, therefore, reflects that there is some uncertainty as to what the target state of the system should be. For example, *options* for the target state may include refuelling an asset to extend its time on station versus sending the asset home and obtaining a replacement.
- *Goals*. This part of the decision ladder refers to the goals of the system. *Goals* serve as quality measures for evaluating different options for the target state. Typically, there are several competing goals and the chosen *goal*(*s*) are the ones that an actor chooses to maximize or preserve in a particular situation. The option that is selected is, therefore, the one that best fulfils the chosen *goal*(*s*) when evaluated against various performance criteria. Examples of *goals* in military air defence may be to minimize the use of fuel or to ensure the safety of assets.
- *Target state*. This part of the decision ladder refers to the system's desired condition, situation or circumstances. The target state reflects the chosen goal(s) and the option that best fulfils the chosen goal(s). For example, a *target state* in military air defence may be to refuel an asset to extend its time on station.
- *Task*. This part of the decision ladder refers to the tasks and resources that are necessary for achieving the target state. For example, the *tasks* necessary to refuel an asset include alerting the air-to-air refueller and directing the asset to the air-to-air refueller, whereas the *resources* necessary to refuel an asset include the availability of an air-to-air refueller.
- *Procedure*. This part of the decision ladder refers to the procedure or sequence of steps that is necessary to achieve the target state. For example, the *procedure* for refuelling an asset safely and effectively may be to alert the air-to-air refueller before directing the asset to it.

To identify the control tasks for a work situation or work function, a number of prompts and generic keywords were developed relating to each part of the decision ladder, which are shown in table 4. For example, for control tasks relating to *alert*, the prompts indicate that analysts should look for events that can act as *alerts* in different work situations or for different work functions. The generic keywords indicate the different guises in which the control tasks may be revealed in a work domain. Therefore, in the case of *alert*, analysts may find that workers refer to seeing, hearing or noticing something or to particular signals, alarms or warnings. As mentioned before, the terminology that is used by workers or in documents will usually be domain-specific, so the reference may be to an 'abort call' instead of to a signal, alarm or warning.

If activity in the system of interest is characterized by both work situations and work functions and control tasks are identified for each work function, further exploration is necessary to determine which sub-sets of the control tasks for each work function are more likely to be active in different work situations. Therefore, analysts should identify which of the control tasks for each work function are more likely to occur in particular work situations. The results of this step can then be used to extend the contextual activity template, as shown in figure 3.

The prompts and keywords that were developed for identifying control tasks may be used with a variety of data collection techniques including: document analysis, observation of daily work activities, walkthroughs, talkthroughs, interviews and

Table 4. Prompts, generic keywords and code words for identifying control tasks.

	Prompts	Generic keywords	Code words
Alert	What kinds of events can act as alerts?	See, hear, notice, detect, signal, alarm, warning	Alert
Information	What kinds of data or facts are available?	Watch, monitor, look out for, search, gather, check, examine, inspect, data, facts, information	Observe; Information
System state	What kinds of assessments about the system's condition or situation are possible with the information?	Recognize, establish, determine, infer, diagnose, interpret, estimate, calculate, figure out, condition, situation, circumstances, status	Diagnose; Current state
Options	What kinds of choices or alternatives are available for the system's desired or target state?	Choose, select, consider, pick, assess, appraise, judge, evaluate, decide, options, choices, alternatives	Evaluate; Options
Goals	What kinds of aims or objectives can be relevant or influence decisions?	Achieve, fulfil, satisfy, accomplish, goals, aims, objectives	Goals
Target state	What kinds of target states are possible?	Same as for options or references to what to do about the current situation or what changes to make to the current situation.	Target state
Task	What kinds of tasks are necessary and what kinds of resources are available?	Plan, designate, allocate, identify, tasks, resources	Plan; Task
Procedure	What kinds of procedures or sequences of steps are necessary?	Schedule, specify, formulate, perform, carry out, conduct, procedures, processes, timings, instructions, tasks, actions	Plan; Procedure

top-down analysis based on work domain analysis and the first part of ConTA. Slight adaptations of the prompts may be necessary for use with different data collection techniques. For example, when conducting interviews, the prompts should be modified into questions that are phrased in terms of the language of the relevant work domain (e.g. Naikar and Saunders 2003).

Table 4 also shows a set of code words that were developed for annotating documents, interview transcripts and other activity records when analysing control tasks. Some of the code words relate to the information processes of a decision ladder, whereas other code words relate to the states of knowledge. Both sets of code words are useful because control tasks are sometimes more apparent as information processes and sometimes more apparent as states of knowledge. For example, sometimes an interviewee may refer to monitoring a situation which would be classified as *observe*, whereas on other occasions an interviewee may refer to particular kinds of information, for example the location of assets or terrain, which would be classified as *information*. The interview transcripts, documents and other activity records may also contain references to shortcuts through the decision ladder, especially when interviewees are recounting specific scenarios or incidents. For coding shortcuts, the records can be annotated with links between code words, for example *observe*-*target state*, if an interviewee relates how the observation of some information immediately led him or her to the target state to be achieved.

4.2.2. AEW&C case study. For AEW&C, control tasks were identified for each of the AEW&C work functions. Figure 5 shows a decision ladder for the AEW&C work function of *manage asset disposition*. In developing decision ladders for AEW&C, the aim was not to specify the actual sequence in which an actor will move through the decision ladder but rather to identify the nature of the key decisions or control tasks relating to each work function. The actual sequence depends very much on the particular situation or scenario and on the skills and knowledge of actors. Nevertheless, a record was kept of movements through the decision ladders if they were mentioned in interviews by domain experts.

Different sub-sets of the *manage asset disposition* decision ladder shown in figure 5 are more likely to be active in different work situations. During the early stages of a mission (enroute to station), the focus may be on monitoring assets or the lower left side of the decision ladder. However, as the mission progresses (on station), the focus may include assessing asset status (upper left of the decision ladder), evaluating options for the number, type and disposition of assets (top part of the decision ladder) and planning and implementing alternative asset configurations (right side of the decision ladder). Towards the end of the mission (enroute to base), the focus may revert to monitoring assets as control is handed over to a replacement AEW&C aircraft. As illustrated in the contextual activity template in figure 3, the different parts of a decision ladder may be shaded to indicate which sub-sets of control tasks are more likely to be active in different work situations.

To develop the AEW&C decision ladders, the decision ladders were first annotated with the control tasks that had been identified in the first step of ConTA (i.e. during the process of defining work functions for AEW&C using the work domain analysis—see previous section). Interviews were then conducted with subject matter experts to identify further control tasks for each of the AEW&C work functions. Specifically, seven military personnel who had considerable knowledge of the AEW&C system concept were interviewed. All of these personnel had operational experience on either the AWACS or E2C systems and/or the equivalent ground-based (as opposed to airborne) operations in the Royal Australian Air Force.

The structure of the interviews was modelled on the Critical Decision Method (Klein *et al*. 1989) in that a series of sweeps was used to gradually move interviewees from an operational description of a work function to the control tasks that were necessary for performing a work function. However, unlike the Critical Decision Method, the interviews were not based on particular scenarios or incidents. In the first sweep, the interviewees were asked to imagine that they were one of the crew on the new AEW&C system and that their job was to perform one of the work functions, for example *manage asset disposition*. They were asked to describe briefly, in 1 or 2 min, what they thought this job would involve. In the second sweep, the interviewees were asked to consider the job in a little bit more detail by describing what they thought their main concerns would be in managing the asset disposition. For instance, some of the concerns that were identified for *manage asset disposition* included: picking up threats at a long range as soon as possible; and positioning assets where they can be effective. In the third sweep, a series of probes based on the prompts described in table 4 were used to identify control tasks in relation to each of the concerns that the interviewees had described. For example, in relation to the concern with picking up threats at a long range as soon as possible, interviewees can be asked 'What types of events can *alert* you to a threat?' or 'What kinds of *options* may be available to you for dealing with a threat?'

The interviews were transcribed and at least two analysts coded each transcript with the code words shown in table 4. In coding the transcripts, each answer given by the interviewees was examined for information relating to all parts of the decision ladder. For example, when asked about procedures, it was often found that interviewees mentioned information that they needed to ascertain to execute a particular procedure. Therefore, in their responses to a probe about procedures, control tasks could be identified relating to both *information* and *procedure*. By doing this, many more control tasks were identified than if one had only searched for control tasks relating to that part of the decision ladder that was the subject of the probe question.

Overall, the interviews were satisfactory for identifying control tasks for AEW&C. However, some of the interviews were difficult, presumably because of the relatively abstract nature of the problem and the 'pressure' of responding quickly in what could have been perceived by some interviewees to be a question-and-answer session. The Critical Decision Method typically involves interviews about memorable scenarios or incidents that interviewees have experienced. Accordingly, previous work has found the Critical Decision Method to be a suitable technique for developing decision ladders for critical points in actual incidents (Naikar and Saunders 2003). However, because AEW&C is a first-of-a-kind system, it was important not to ask interviewees about their experiences in older or existing systems but wanted to explore how they could work in the new system.

A technique that may be more suitable for eliciting information about control tasks in new systems is table-top analysis (Kirwan and Ainsworth 1992, Naikar *et al*. 2003). This technique requires a group of experts with knowledge of the system under consideration; in the case of AEW&C the experts may include operations personnel, military strategists and engineers. During table-top discussions, experts can explore, in a problem-solving and explanatory way, the control tasks that are necessary for the various work situations and/or work functions. The Critical Decision Method format that was described for the AEW&C interviews could still be used as a framework for facilitating discussions. In addition, the discussions could be based around problem descriptions that represent the kinds of situations in which the new system may be involved (Kirwan and Ainsworth 1992, Dekker and Woods 1999, Naikar *et al*. 2003). Preliminary investigations with table-top analysis indicate that it may provide a more suitable format than interviews for identifying control tasks for new systems.

5. General discussion

This paper has contributed to developing a coherent approach to ConTA. The paper has discussed the different approaches to ConTA (Rasmussen *et al*. 1994, Vicente 1999) and presented a consolidated approach that reinstates the analysis of work situations and work functions as a critical element of the analysis of activity in the CWA framework. In addition, the paper has extended the basic concepts for ConTA by discussing the special case of work systems for which activity is best characterized as a combination of work situations and work functions and by presenting a new formative representation, called the contextual activity template, for modelling activity in these work systems. The paper has also presented a set of methodological guidelines for performing ConTA.

The conceptual and methodological approach to ConTA presented in this paper was developed through work with complex, military systems. This approach may be useful for analysing other systems that share the characteristics of military domains that are listed in table 1. Further research is necessary to determine whether this approach can be extended to other kinds of systems.

Finally, the paper presented a case study of a ConTA for AEW&C. This case study demonstrated the conceptual extensions and methodological guidelines for ConTA by example. In addition, the case study highlighted some of the difficulties of conducting ConTA for first-of-a-kind, complex systems during the early stages of development.

The difficulty of analysing cognitive work in future systems has been described as the 'envisioned world problem' by Dekker and Woods (1999). To tackle this problem, Dekker and Woods studied how experts solved future incidents using airspace maps depicting future airspace layouts, static representations of future radar displays and future procedures. However, for systems at the very early stages of development, like AEW&C, these artefacts may not be available and may in fact be the desired design outputs of a work analysis. Waiting for further design and development to occur incurs the risk that the system may be constrained by the technical solution. To resolve this problem, the authors are currently investigating the use of table-top analysis techniques to analyse cognitive work in future systems based on a discussion of future incidents or problems, independently of the underlying technology. Validation of the cognitive work requirements should occur as soon as mock ups and prototypes of the future system become available.

Notes

1. Rasmussen *et al*. (1994) describe work functions as problems to solve. A previous paper (Naikar *et al*. 2003) used the term work problems instead of work functions.
2. This type of analysis for a military system was previously referred to as temporal co-ordination control task analysis (Sanderson and Naikar 2000). The contextual activity template accommodates spatial as well as temporal constraints and it illustrates the co-ordination of work situations and work functions as well as control tasks.

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