Designing Teams for First-of-a-Kind, Complex Systems Using the Initial Phases of Cognitive Work Analysis: Case Study

Neelam Naikar, Brett Pearce, and **Dominic Drumm,** Defence Science and Technology Organisation, Melbourne, Australia, and **Penelope M. Sanderson,** Swinburne University of Technology, Melbourne, Australia

We present a technique for team design based on cognitive work analysis (CWA). We first develop a rationale for this technique by discussing the limitations of conventional approaches for team design in light of the special characteristics of first-of-a-kind, complex systems. We then introduce the CWA-based technique for team design and provide a case study of how we used this technique to design a team for a first-of-a-kind, complex military system during the early stages of its development. In addition to illustrating the CWA-based technique by example, the case study allows us to evaluate the technique. This case study demonstrates that the CWA-based technique for team design is both feasible and useful, although empirical validation of the technique is still necessary. Applications of this work include the design of teams for first-of-a-kind, complex systems in military, medical, and industrial domains.

INTRODUCTION

Cognitive work analysis (Rasmussen, Pejtersen, & Goodstein, 1994; Vicente, 1999) has most commonly been used for the analysis, design, and evaluation of interfaces for complex sociotechnical systems (e.g., Burns, 2000; Dinadis & Vicente, 1999; Lintern & Naikar, 2002; Rasmussen, 1998; Vicente, 1995). Recently it has been suggested that the use of cognitive work analysis (CWA) can be extended beyond interfaces to the entire system and to all phases of the system life cycle, from requirements definition to decommissioning (Hori, Vicente, Shimizu, & Takami, 2001; Sanderson, Naikar, Lintern, & Goss, 1999). Some support for this claim exists in the form of detailed case studies that have used CWA at particular stages of the system life cycle – for example, for developing specifications (Leveson, 2000), evaluating system designs (Naikar & Sanderson, 2001), and analyzing training needs (Naikar & Sanderson, 1999).

In this paper we show that CWA can also be used for designing teams. In particular, we describe a technique or process for using CWA to design teams for complex systems. Although CWA of complex systems has been conducted several times before, a process for using CWA to design teams has not been developed or specified previously. As we will show later, this process for team design is different from how CWA has been used in the past to develop interface designs.

In developing a technique for team design, our focus was on first-of-a-kind systems (Roth & Mumaw, 1995). First-of-a-kind systems have no close existing analogues because, for example, technological advances have led to vastly improved functionality as compared with older-generation systems. Thus the behavior of workers in the new system cannot be inferred entirely from that of workers in existing systems. More specifically, we focus on designing teams for first-of-a-kind, complex systems at the earliest stages of development, when the systems exist only as concepts on paper. Because the systems have not yet been prototyped or built and populated with workers, detailed information about

Address correspondence to Neelam Naikar, Defence Science and Technology Organisation, P.O. Box 4331, Melbourne, VIC 3001, Australia; neelam.naikar@dsto.defence.gov.au. **HUMAN FACTORS,** Vol. 45, No. 2, Summer 2003, pp. 202–217.

the behavior of workers in these systems is unavailable.

An advantage of designing teams during the concept stage of system development is that the team design can be tailored to the work demands of the proposed system. As system development proceeds, the technical system design becomes more "locked in," and the team design is more likely to be constrained by the technical solution. Specifying a team design during the early stages of development also enables systems developers to engineer the technical system so that it best supports the work structure and work processes of the team members who will be working with the system. Although trade-offs may be necessary if current technology cannot support the proposed team design, the focus is more likely to remain on how best to support the team of workers in the system, given the available technology.

Conventional Approaches to Team Design

Conventional approaches to team design span a variety of disciplines, including engineering (Davis & Wacker, 1982, 1987; Mundel, 1985; Niebel, 1988), social and organizational psychology (Hackman & Oldham, 1980; Medsker & Campion, 1997; Sundstrom, De Meuse, & Futrell, 1990), and engineering psychology (Dieterly, 1988; Dubrovsky & Piscoppel, 1991; Lehner, 1991). Although these approaches differ in their theoretical orientations and values, they are all based on an analysis of the work requirements of the relevant system. Once complete, the work analysis is used to make decisions about the size of the team, the structure of the team (e.g., its hierarchical organization and decomposition into subteams), the roles and responsibilities of team members, and the skills and training of team members. The aim is to design a team that best fulfills the work requirements of the system.

Conventional approaches to team design have been useful for designing teams for existing systems (Medsker & Campion, 1997). However, for two main reasons, they cannot readily be applied to first-of-a-kind, complex systems at the concept stage of development. First, conventional approaches to team design rely on methods for work analysis that require an existing work system. These methods involve observing and measuring workers in their actual work spaces (e.g., time to complete tasks), surveying equipment at work sites, examining existing procedures and manuals, and using interviews or questionnaires to ask workers, supervisors, and managers about the details of their jobs.

At the concept stage of development, however, the proposed work system does not exist in a physical form – a situation that has been described as the "envisioned world problem" by Dekker and Woods (1999). Waiting until a physical work system is in place may lead to team designs that are constrained by the technical solution. Alternatively, inferring the behavior of workers in the proposed system by studying older-generation, existing systems may lead to team designs that incorporate undesirable work patterns from the older technology or that do not tap into desirable work patterns offered by the new technology (Roth & Mumaw, 1995; Vicente, 1999).

Second, conventional approaches to team design rely on methods of work analysis that describe the work requirements of a system in terms of stable sets of tasks or procedures. However, workers in complex systems often develop new ways of working with a technology as they gain experience with it. Thus it is difficult to specify the full set of work procedures before a system is put into operation.

Workers in complex systems also invent new ways of working to deal with novel contingencies. Hence it is difficult to specify stable sets of tasks or procedures for dynamic or unanticipated events. This type of work analysis is likely to be incomplete (Meister, 1996; Rasmussen et al., 1994; Vicente, 1999). Conventional approaches may therefore lead to team designs that are not well suited to tasks or procedures that could not be specified in advance.

A CWA-Based Technique for Team Design

In this paper we propose a technique for team design based on CWA (Rasmussen et al., 1994; Vicente, 1999). CWA is a formative approach to work analysis that explicitly recognizes that workers in complex systems have a large number of potential work patterns for dealing with both routine and novel situations and that not all of these patterns can be specified in advance. Hence rather than describing the work requirements of a system in terms of stable sets of tasks or work procedures, CWA focuses on work domain and cognitive constraints that shape workers' behavior in the first place. These constraints or boundaries can embrace a wide variety of work patterns in a dynamic work space, including work patterns that may be difficult to anticipate. Moreover, the analysis of constraints can take place in the absence of a physical work system. CWA therefore offers a framework for designing teams for first-of-a-kind, complex systems at the concept stage of development.

Although CWA has not previously been used for team design, it is an approach that is explicitly tailored for the analysis, design, and evaluation of complex sociotechnical systems (Vicente, 1999). These are systems that typically have high levels of automation for dealing with routine situations. The central role of human workers in these systems therefore is to deal with novel situations and local conditions that cannot be foreseen by designers. The philosophy of CWA is to uncover the requirements that will help workers to be flexible, adaptive problem solvers in unpredictable situations. Embedding these requirements in information support will give workers the flexibility to adapt to these situations and thereby to preserve system performance and safety.

Similarly, designing teams that are tailored to these requirements should give teams the flexibility to adapt to local conditions and novel situations. Providing this type of flexibility in teams is consistent with accumulating evidence that flexible team structures are highly effective for dealing with dynamic and unpredictable environments (Hutchins, 1990; La Porte & Consolini, 1991; Paris, Salas, & Cannon-Bowers, 2000; Rochlin, 1989; Stammers & Hallam, 1985).

CWA consists of five phases of analysis that focus on different kinds of constraints. *Work domain analysis* focuses on the physical and purposive environment of the system; *activity analysis in work domain terms and decision-making terms* (or *control task analysis*) focuses on what needs to be done in the work domain; *strategies analysis* focuses on strategies or processes for carrying out the activity; *socio-organizational analysis* focuses on the coordination of workers; and *worker competencies analysis* focuses on the capabilities required by workers to perform the work of the system. Each phase therefore gradually shifts from ecological to cognitive constraints, the argument being that the fundamental constraints on system performance are ecological and that a design must first be compatible with the constraints of the environment before it is useful to ensure that the design is compatible with human cognitive constraints (Vicente, 1999).

In this paper we present a technique for team design based on work domain analysis and on activity analysis in work domain terms. The aim of this technique is to develop a team design that is compatible with the ecological constraints of the work domain – that is, with the physical and purposive environment of the system and with what needs to be done in the work domain. Once ecological compatibility has been achieved, the remaining phases of CWA can be performed to ensure that the team design is compatible with cognitive constraints, which includes defining the distribution of control tasks or decisions and strategies across people and machines, as well as the competencies required by people to fulfill their responsibilities. These analyses may be performed after the system concept has been outlined and more detailed definition of the system design begins. Empirical evaluation of the team design should be conducted when mockups, prototypes, or simulations of the proposed system become available.

The CWA-based technique for team design that we present in this paper involves three main steps. The first involves conducting a work domain analysis to capture (a) the functional purposes or high-level objectives of the proposed work system, (b) the priorities and values that must be preserved during system operation, (c) the general functions that the system must coordinate and/or execute to fulfill its functional purposes, (d) the physical functions or functionality afforded by the physical devices of the system, and (e) the physical form or physical devices of the proposed work system. This information may be gleaned from documents describing the system concept and from subject matter experts who were involved in defining the system concept.

The second step is to conduct an activity analysis in work domain terms (Rasmussen et al., 1994). Here the focus is on identifying the set of *work situations* in which workers will be required to participate or the set of *work problems* (Rasmussen et al. used the term *work functions,* which they described as "problems to solve") that workers will be required to solve in order to fulfill work domain constraints. For this phase of analysis work domain analysis provides a useful structure for exploring the situations or problems that workers will be required to deal with to fulfill the purposes, priorities and values, and general functions of a work domain, given the set of physical resources. A detailed knowledge of the system concept and the involvement of subject matter experts are necessary inputs to this process.

The third step is a tabletop analysis (Kirwan & Ainsworth, 1992) that utilizes the work domain analysis and the activity analysis to explore the feasibility of alternative team designs for a proposed work system. Tabletop analysis is consistent with a formative approach to work analysis because it supports an examination of how work *can* be done rather than how work *is* currently done (descriptive approach) or how work *should* be done (normative approach).

The tabletop analysis involves (a) specifying the team concepts to examine, including team design variables (e.g., team size, number of levels of hierarchy) and plausible values for each variable, (b) designing scenarios that are representative of the kinds of situations that the proposed system may encounter, (c) holding discussions with subject matter experts to explore how the work demands of the scenarios can be distributed across team members given different team concepts, (d) translating the distribution of scenario-specific work demands for each team concept into a distribution of work problems from the activity analysis, and (e) using the work domain analysis to evaluate the alternative team concepts in terms of how well the alternative distributions of work problems support the functions, priorities and values, and purposes of a work domain, given the set of physical resources. The insights gained from this fifth step lead to requirements for a new team design.

This process for using CWA for team design is significantly different from how CWA is used for interface design. For interface design both work domain analysis and activity analysis provide models of the information that must be made available to workers in designing information support systems (e.g., Burns, 2000; Dinadis & Vicente, 1999; Lintern & Naikar, 2002). For team design activity analysis is used for characterizing the activity of workers in different scenarios as a function of alternative team concepts, and work domain analysis is used for evaluating the alternative team concepts.

CASE STUDY

Having outlined some of the theoretical motivations for a CWA-based technique for team design, we now offer a case study that shows how we used this technique to design a team for a first-of-a-kind, complex military system called Airborne Early Warning and Control (AEW&C). This case study allows us to illustrate the CWA-based technique by example and also to evaluate the technique. We begin by providing some information about AEW&C.

AEW&C is a complex airborne system that is being developed by Boeing for the Australian Defence Force. This acquisition contract was signed in December 2000, and the first aircraft is scheduled for delivery in 2008. When it is operational, AEW&C will be staffed in the cabin of the aircraft by a team of people who will be responsible for developing a tactical picture of an allocated area of operations and for coordinating the activities of defense assets in that area. This role is similar to that of the Airborne Warning and Control System (AWACS) of the U.S. Air Force and the E2C system of the U.S. Navy. AWACS has 19 crew members in the cabin of the aircraft, whereas E2C has 3 crew members.

AEW&C will have technology that is vastly different from that in AWACS and E2C. In particular, it will have digital technology, whereas AWACS and E2C have analog technology. Digital technology offers significantly greater flexibility in operations. For example, the radar on AEW&C can be stopped, started, and made to "stare" at targets of interest at will, whereas the radars in AWACS and E2C are bound to a fixed number of revolutions per minute. Compared with AWACS and E2C, AEW&C will also have significantly greater computing power, higher levels of data fusion, and more automation, including automatic radar tracking, radar operation, and situation and threat assessment.

A key concern of members of the AEW&C System Program Office, the main Australian Department of Defence organization responsible for AEW&C acquisition, was the design of the AEW&C team in the aircraft cabin. Some issues that the program office personnel were particularly concerned about were the size of the AEW&C team, the number of levels of hierarchy in the team, whether the team should be decomposed into subteams, and whether workers should have dedicated roles and responsibilities or be multiskilled. In the following sections we show how we used the CWA-based technique to address these issues. We begin by describing the AEW&C work domain analysis and activity analysis and then show how we used tabletop analysis to explore the feasibility of alternative team designs for AEW&C.

AEW&C Work Domain Analysis

To conduct a work domain analysis for AEW&C, we relied on documents that described the AEW&C system concept and on input from subject matter experts. The documents included the *AEW&C Concept of Operations* and the *AEW&C System Specification.* Subject matter experts included military personnel, engineers, operations analysts, and defense scientists who had been involved in defining the AEW&C system concept. The documents were sufficient for identifying a preliminary set of work domain constraints, which we represented in an abstraction hierarchy, the main modeling formalism for work domain analysis (Figure 1). We subsequently used this representation as a basis for discussions with subject matter experts in order to refine the analysis. The AEW&C work domain analysis was conducted over a period of 6 months, with two analysts working half time.

In reviewing the documents and interviewing subject matter experts, we used the generic labels and descriptions of work domain constraints (Rasmussen et al., 1994; Vicente, 1999) to guide our search for particular kinds of information. For the functional purposes of AEW&C, we searched for information about why AEW&C was purchased by the Australian Defence Force and how it would contribute to Australia's defense capability. For the priorities and values of AEW&C, we looked for information about the edge that AEW&C was expected to offer over potential adversaries in the area. For its general functions, we looked for information about the everyday functions that AEW&C would perform on missions to fulfill its functional purpose. Information about the physical functions and physical form of AEW&C was readily available in documents, in particular the *AEW&C System Specification,* which listed the physical devices of AEW&C and the functionality of each device.

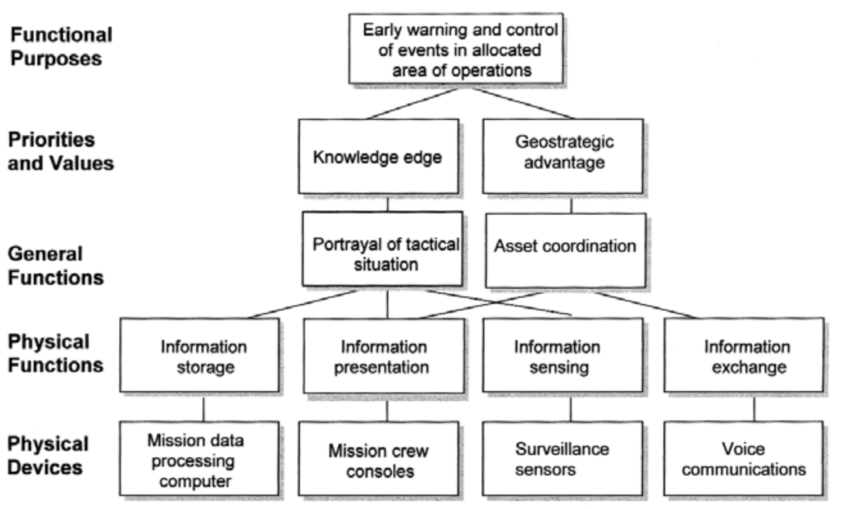

Figure 1. A sample of functions from each layer of the AEW&C abstraction hierarchy.

Figure 1 shows a sample of functions from each layer of the AEW&C abstraction hierarchy and the links between the layers. This figure is slightly different from the AEW&C abstraction hierarchy presented elsewhere (Naikar & Sanderson, 2001). In our original representation the functions in the abstraction hierarchy tended to be misinterpreted as activity. Consequently, we have reworked the descriptions in each layer to emphasize the structural properties of the work domain. We have done this, first, by focusing on the objects of action in the work domain and, second, by using nouns rather than verbs to characterize the functional properties of AEW&C (Vicente, 1999).

In Figure 1, the links represent means-ends or "why-how" relations. If you focus your attention on a function at a particular layer and ask, "Why is this function performed?" the answer is found in the functions to which it is linked at the layers above. If you ask, "How is this function performed?" the answer is found in the functions to which it is linked at the layers below. In addition, we developed detailed descriptions of each of the functions and links in the AEW&C abstraction hierarchy and decomposed each of the functions into its constituent parts. For example, "portrayal of tactical situation" was decomposed into types of tactical information, including behavior of other entities, intelligence, weather, and terrain.

AEW&C Activity Analysis in Work Domain Terms

For this phase of analysis, Rasmussen et al. (1994) suggested identifying either the work situations that workers will be required to participate in or the work problems that workers will be required to solve. For AEW&C we found it useful to combine the two. Based on our knowledge of the AEW&C system concept acquired during the work domain analysis, we identified a preliminary set of work situations and work problems for AEW&C. Following that, we worked with subject matter experts to refine our preliminary analysis, in particular to minimize the overlap between the work problems and to develop extended descriptions of each work problem. The AEW&C activity analysis in work domain terms was conducted over a period of 2 months, with one analyst working half time.

Figure 2 shows the final set of AEW&C work problems against a backdrop of AEW&C work situations. The work situations, shown along the horizontal axis, are the different phases of a mission. The work problems are shown along the vertical axis. Some work problems can occur in more than one mission phase, as indicated by the boxes surrounding these work problems. To clarify what the problem is that workers have to solve, we have extended descriptions of the labels in the figure. For example, for the label "manage crew," the problem is "to distribute responsibilities, assets, and other resources among crew in order to support the aims of the mission under changing tactical and environmental conditions."

To develop the representation in Figure 2, we first determined that the recurring work situations for AEW&C constitute the different phases of a mission. After that we analyzed the work problems that AEW&C workers will be required to solve in order to fulfill work domain constraints. That is, we asked ourselves and the subject matter experts what problems AEW&C workers will be required to solve given each of the purposes, priorities and values, functions, and physical resources of AEW&C. For example, to fulfill the general function of "asset coordination," we identified that AEW&C workers will be required to solve the work problem of "manage asset disposition," which includes determining what kinds of assets are required, how many of each kind of asset is required, where they are to be positioned, and what their specific objectives are. After defining the work problems, we identified all of the mission phases in which the work problems can occur.

The process of identifying work problems involved thinking about what AEW&C workers will be required to do in terms of problems to solve rather than the tasks that are necessary for solving problems. Tasks typically involve activities such as observing information, assessing situations, evaluating goals, planning, and executing procedures. Focusing on tasks was actually more natural to us. For example, with respect to the work problem that we eventually labeled as "manage crew" (see the definition given earlier for this work problem), our tendency

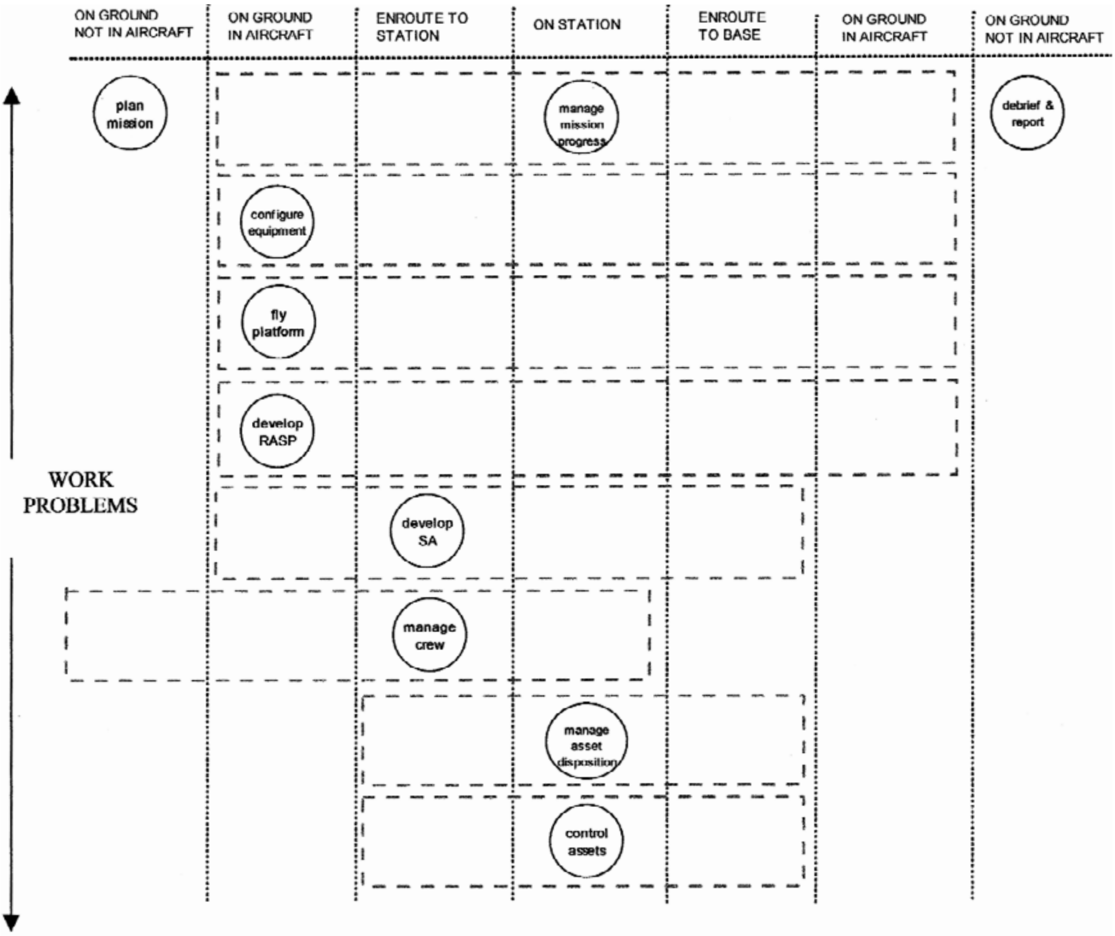

Figure 2. The AEW&C activity analysis in work domain terms (RASP = recognized air surface picture; SA = situational awareness).

was to identify tasks such as monitoring crew, scheduling rest periods for crew, and allocating particular duties to crew members. Whenever we found ourselves thinking at the level of tasks, we considered what problem AEW&C workers were solving by performing the tasks or the reason for which they were performing the tasks. This process resulted in a definition of the work problem.

AEW&C Tabletop Analysis

The tabletop analysis involved using the AEW&C work domain analysis and activity analysis to explore the feasibility of alternative team designs for AEW&C. In the rest of this section we describe the steps involved in conducting the tabletop analysis for AEW&C. These steps include (a) identification of team concepts, (b) scenario design, (c) tabletop sessions, (d) translation of scenario-specific work demands into work problems, and (e) evaluation of team concepts and generation of requirements for a new team design. Thus the first two steps involve preparing for the tabletop sessions (the third step), whereas the fourth and fifth steps involve analyzing the tabletop sessions. Each tabletop analysis takes approximately 5 days.

Identification of team concepts. The first step involved identifying the team design variables that the AEW&C System Program Office personnel wanted to examine and the set of values for each variable that were plausible for AEW&C. Figure 3 shows, for example, that for the variable of team size, values between 6 and 10 were judged to be most plausible by the subject matter experts and the analysts. Each pathway, which

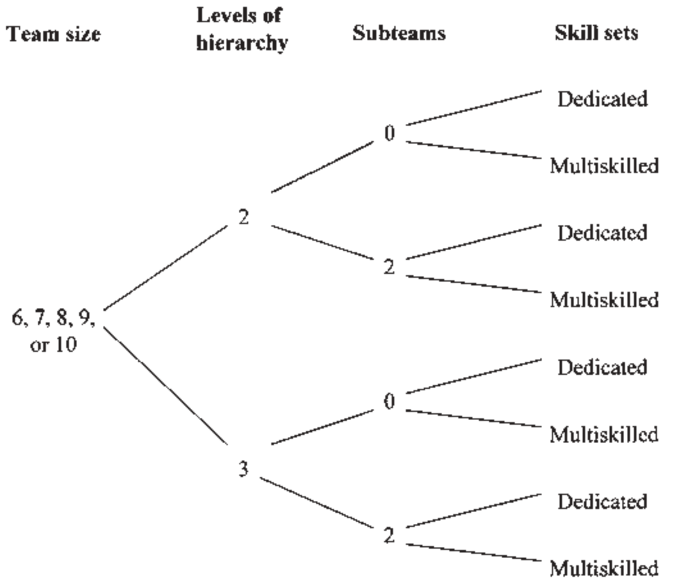

Figure 3. The team design variables for AEW&C (team size, levels of hierarchy, subteams, skill sets) and the set of plausible values for each variable. Each pathway specifies a particular team concept.

consists of different combinations of values across the four variables, specifies the alternative team concepts to explore with the tabletop analysis. However, it may not be necessary to examine all of the team concepts. For example, after performing a tabletop analysis for a team size of 8, it may become evident that team sizes of 9 and 10 are unnecessarily large for the proposed system.

Scenario design. The second step involved working with Australian Defence Force personnel to develop air defense scenarios that were representative of the kinds of missions in which AEW&C might be involved. We developed scenarios that were considered routine for AEW&C (e.g., conducting general surveillance in the northern regions of Australia) as well as scenarios representing more exceptional circumstances (e.g., supporting allied forces during battle). We identified critical events in the scenarios (e.g., strike package enters no-fly zone, hostile firing on friendly ships), which we defined as events that required some response (actions, decisions) from team members, and we constructed timelines for the critical events.

Tabletop sessions. In the third step we worked with subject matter experts to explore how the scenarios could be handled with alternative team concepts. These experts were two Australian Defence Force operational personnel who were involved in developing the AEW&C concept of operations and who had at least 1 year of experience as crew members for AWACS or E2C. Both participated in each tabletop session.

After we selected a team concept and a scenario for the session, we took the subject matter experts through each of the critical events in the scenario and asked them to describe how they could deal with those critical events, given the team concept that was available to them. In particular, we were interested in identifying the work demands associated with the critical events and how these demands could be distributed across team members. On a whiteboard we kept a record of the allocation of work demands to team members as a function of the critical events; the team members were shown in rows, the critical events were shown in columns, and the cells contained a description of the work demands that each team member was allocated as a function of the critical events in the scenario.

We also asked the subject matter experts about the criteria they used for allocating work demands to team members. Some of the criteria they identified included judgments of the workload of individual team members, the information that particular team members had access to, the similarity of new work demands to the existing responsibilities of team members, and their predictions of the likely future demands of the mission. In addition, we asked the experts to describe the communication and coordination requirements for allocating work demands to team members.

Translation of scenario-specific work demands into work problems. In the fourth step we translated the work demands that the subject matter experts had described into work problems from the AEW&C activity analysis in work domain terms. For example, a work demand that involved “directing fighter aircraft to conduct a sweep of Location X” was translated into the work problem of “control assets,” whereas a work demand that involved “changing the radar search pattern” was translated into the work problem of “configure equipment.” We used the extended descriptions that we had developed of the work problems (during the activity analysis in work domain terms) to guide which work problems the work demands should be translated into.

The resulting representations therefore described the distribution of work problems (rather than work demands) to team members as a function of critical events. Translating the work demands (which the subject matter experts had described in very scenario-specific terms) into work problems that were common to all scenarios allowed us to more easily compare the team concepts across different scenarios (i.e., in the final step of the tabletop analysis). In addition, the work problems allowed us to express the distribution of work in the scenarios in terms of a set of constraints that can accommodate a large variety of sequences of tasks or trajectories in workers’ behavior.

Our representations of the distribution of work problems for an entire scenario are too large to be reproduced legibly here. However, in Figures 4 and 5 we provide a small section from two of our representations to illustrate the distribution of work problems to team members in the same scenario for two different team concepts. The main difference between the two concepts is team size: 10 in Figure 4 and 6 in Figure 5. In these representations the critical events in the scenario are described in the columns (e.g., dividing electronic support [ES] sectors, identifying tracks of interest, control of P3C); the roles of each of the team members are described in rows (e.g., mission commander, fighter controller); the work problems that team members are allocated are described in the circles (e.g., configure equipment, control assets); and the communication and coordination associated with the reallocation of work problems are shown with arrows (the arrows are numbered and described in the captions for these figures).

The rows that are shaded in Figure 5 represent those individuals in the 10-person team who are not available in the 6-person team. The bold circles in Figure 5 represent the added responsibilities of team members in the 6-person team, given the reduction in team size from 10 to 6; thus these are work problems with which the corresponding team members in the 10-person team did not have to deal.

Evaluation of team concepts and generation of requirements for a new team design. In the final step we used the AEW&C work domain analysis to evaluate the different team concepts and to generate requirements for a new team design. Table 1 provides a sample of our findings from this step of a tabletop analysis. The scenario for this example was an 8-h mission involving high-level conflict, in which AEW&C was tasked with focal area surveillance of a no-fly zone of Country X and broad area surveillance of a maritime region. The team concepts we analyzed in this example include (a) a 6-person team with two levels of hierarchy, no subteams, and workers with dedicated roles and responsibilities; (b) a 6-person team with two levels of hierarchy, no subteams, and multiskilled workers; (c) a 10-person team with two levels of hierarchy, no subteams, and workers with dedicated roles and responsibilities; and (d) a 10-person team with two levels of hierarchy, no subteams, and multiskilled workers. Thus the main differences between the team concepts in this example are the number of people in the team and whether workers are dedicated or multiskilled.

To evaluate the different team concepts, we first identified differences in the distribution of work problems for alternative team concepts or recurring patterns in the distribution of work problems for alternative team concepts (e.g., column 1 of Table 1). We typically focused on differences and recurring patterns relating to the number of team members allocated to each work problem, the number and combination of work problems allocated to each team member, the number and types of instances in which work problems had to be reallocated or reshuffled among team members, and the communication and coordination requirements associated with reallocating work problems to team members. The subject matter experts and analysts then considered what impact these differences and recurring patterns might have on each of the physical resources, functions, priorities and values, and purposes of the AEW&C work domain (e.g., column 2 of Table 1).

Finally, on the basis of these judgments, we generated requirements for a new AEW&C team design (e.g., column 3 of Table 1). In developing requirements, our aim was to minimize the negative impact or enhance the positive impact of particular team concepts on the AEW&C work domain.

Although some of the findings in Table 1 may seem obvious in hindsight, not all of them had occurred to the analysts and subject matter experts prior to the analyses. In cases in which we had foreseen how the distribution of work problems might differ for the alternative team concepts (i.e., that individuals in the 10-person teams would be allocated fewer work problems than would those in the 6-person teams and that of the two 6-person teams, more team members in the multiskilled team than in the dedicated team would be controlling and managing assets), we had not explicitly considered what impact these differences may have on the AEW&C work domain. Moreover, some of the findings were surprising to the subject matter experts (e.g., that there was no reallocation or reshuffling of work problems in the multiskilled teams and how heavily tasked the mission commander was with housekeeping responsibilities).

AEW&C Team Design

To design the AEW&C team, the analysts studied the requirements for team design from all the tabletop analyses and created a team design that fulfilled those requirements. This team design specifies that the team should not be split into subteams and that team members should be multiskilled. In addition, the team design specifies flexibility in team size (6 or 7) and in the number of levels of hierarchy (2 or 3). Hence the AEW&C team design can be adapted to different situations.

For instance, from the tabletop analyses we identified the need for a deputy mission commander to assist the mission commander with housekeeping responsibilities in scenarios with reasonably complex work demands. In our team design the role of deputy mission commander is a flexible one that is implemented when the mission commander needs to be buffered from micromanagement. On missions or even segments of missions when this buffer is not required, the person in this role can either take up other responsibilities (e.g., maintain the tactical picture, control assets) or be used for crew rotation. These configurations allow variations to both team size and the number of levels of hierarchy.

When we presented this team design to the AEW&C System Program Office, military personnel (including those with backgrounds in AWACS and E2C operations) judged that this team design was better than the designs they had independently considered for AEW&C in the past. As a result, the team design that we developed has been adopted by the AEW&C System Program Office for AEW&C operations. In addition, our analyses have led to modifications of the AEW&C technical solution concept so that it better supports AEW&C teamwork. These alterations were made prior to the contract's being signed with Boeing and therefore at no cost to the Commonwealth of Australia. Future work will involve performing the remaining three phases of CWA for AEW&C to ensure that the team design is compatible with the cognitive constraints of the work domain.

Evaluation of the CWA-Based Technique for AEW&C Team Design

The CWA-based technique allowed us to propose a team design for AEW&C in the absence of a physical work system. If we had to wait until a physical work system for AEW&C was in place, the AEW&C team design might have been constrained by the technical solution. Alternatively, if we had relied on conventional approaches to

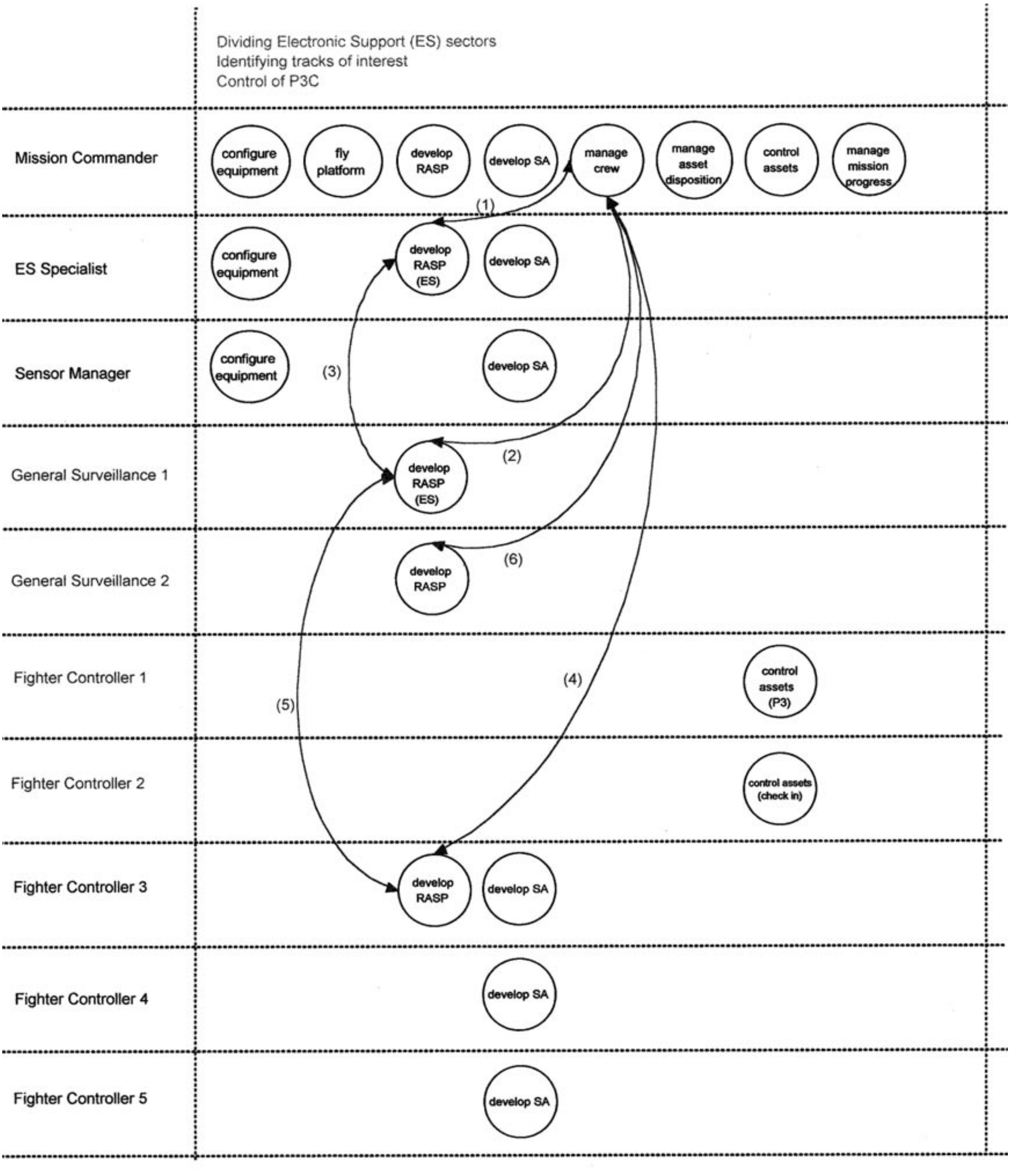

Figure 4. A small section of the distribution of work problems to team members for a 10-person team with two levels of hierarchy, no subteams, and multiskilled workers. Arrow annotations: (1) ES specialist discusses the need for additional ES support with the Mission Commander; (2) Mission Commander directs General Surveillance 1 to assist with ES analysis; (3) the ES specialist negotiates the distribution of ES analysis with General Surveillance 1; (4) Mission Commander asks Fighter Controller 3 to assist with developing RASP; (5) General Surveillance 1 hands over the work problem of developing RASP to Fighter Controller 3 (briefing on outstanding tasks, identifying significant details, etc.); (6) Mission Commander informs General Surveillance 2, who is also performing development of RASP, of this change to tasking. (ES = electronic support; RASP = recognized air surface picture; SA = situational awareness.)

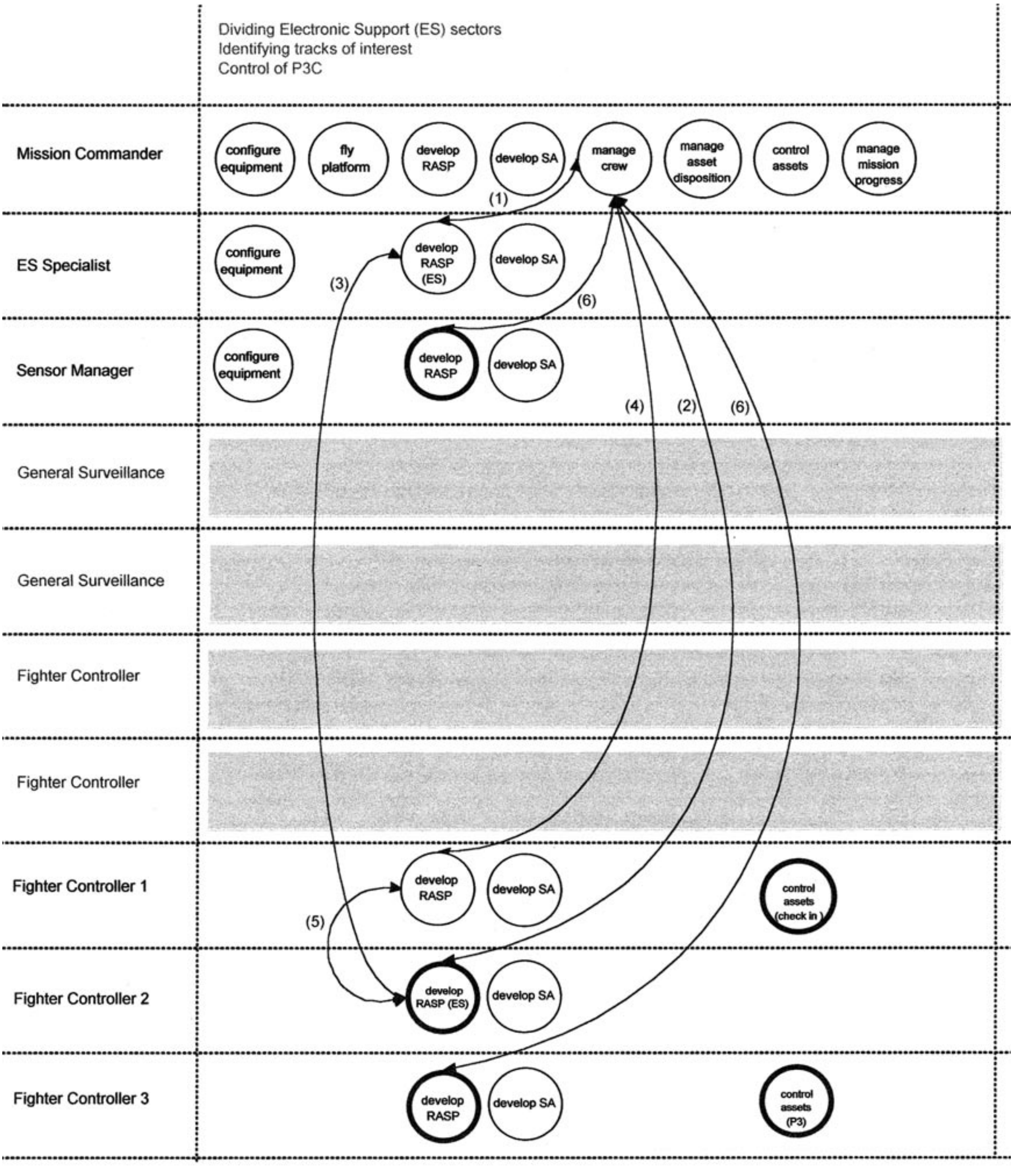

Figure 5. A small section of the distribution of work problems to team members for a 6-person team with two levels of hierarchy, no subteams, and multiskilled workers. Arrow annotations: (1) ES specialist discusses the need for additional ES support with the Mission Commander; (2) Mission Commander directs Fighter Controller 2 to assist with the ES analysis; (3) ES specialist negotiates the distribution of ES analysis with Fighter Controller 2; (4) Mission Commander asks Fighter Controller 1 to assist with developing RASP; (5) Fighter Controller 2 hands over the work problem of developing RASP to Fighter Controller 1 (briefing on outstanding tasks, identifying significant details, etc.); (6) Mission Commander informs the Sensor Manager and Fighter Controller 3, who are also performing development of RASP, of this change to tasking. (ES = electronic support; RASP = recognized air surface picture; SA = situational awareness.)

TABLE 1: A Sample of Findings from a Tabletop Analysis for AEW&C

Differences and Recurring Patterns in the Distribution of Work Problems for Alternative Team Concepts	Impact on AEW&C Work Domain	Requirements for AEW&C Team Design
Individuals in the 10-person teams were preoccupied with fewer work problems than individuals in the 6-person teams.	• The subject matter experts judged that workload in the 10-person teams was low. If workload is very low, team members may become bored and vigilance may be low (Huey & Wickens, 1993). Low vigilance is most likely to lead to detriments in routine activities, such as general maintenance of the tactical picture. Thus in the 10-person teams, the purpose-related function of portraying the tactical situation and the priority and value of maintaining a knowledge edge may be compromised. • The subject matter experts judged that workload in the 6-person teams was high. Under high-workload conditions in which some tasks are shed or compromised in favor of others (Huey & Wickens, 1993), general maintenance of the tactical picture is likely to be perceived as less urgent than coordinating and protecting valuable assets in a hostile airspace. Thus in the 6-person teams, the purpose-related function of portraying the tactical situation and the priority and value of maintaining a knowledge edge may be compromised.	In scenarios with relatively complex work demands, a 10-person team may be too large for AEW&C, whereas a 6-person team may be too small. Thus a 7- or 8-person team may be suitable for AEW&C.
In the two multiskilled teams, in which work problems could have been reshuffled from one role to another, there were no instances of work reallocation.	With respect to the potential for work reallocation, there was no benefit of multiskilling to the AEW&C work domain in this case. In the 10-person team there was so much spare capacity that work problems did not have to be shuffled among team members; there was always a spare team member for dealing with a new work demand. In the 6-person team, all team members were always preoccupied with several work problems; thus there was little spare capacity for the team to reorganize their work responsibilities in response to local contingencies.	To fully realize the benefits of multiskilling, a team size of 7 or 8 may be more suitable for AEW&C.
Of the two 6-person teams, at least one crew member in the dedicated team was always devoted to general maintenance of the tactical picture throughout the scenario. In the multiskilled team, individuals who were responsible for general maintenance of the tactical picture were also controlling and managing assets at critical points in the scenario.	In the 6-person dedicated team not all of the team members were trained for controlling and managing assets, so there was always at least one team member devoted to general maintenance of the tactical picture. However, in the 6-person multiskilled team there was a tendency to use all of the team members for both controlling and managing assets and general maintenance of the tactical picture. Because of the demands associated with protecting valuable assets in a hostile airspace, the 6-person multiskilled team may find it more difficult than the 6-person dedicated team to fulfil the purpose-related function of portraying the tactical situation and to maintain the priority and value of a knowledge edge.	In reasonably complex scenarios, the primary responsibility of at least one team member in a small multiskilled team should be general maintenance of the tactical picture.

Of the two 6-person teams, more team members in the multiskilled team than in the dedicated team were allocated to controlling and managing assets. This was because all of the team members in the multiskilled team, compared with just three team members in the dedicated team, were trained for controlling assets.	As the greatest demands in this scenario were those associated with controlling and managing assets, subject matter experts judged that workload in this scenario was more evenly distributed in the 6-person multiskilled team than in the 6-person dedicated team. Thus the 6-person dedicated team may find it more difficult than the 6-person multiskilled team to fulfil the purpose-related function of asset coordination and to maintain the priority and value of a geostrategic advantage.	In small teams, team members should be multiskilled so that workload can be more evenly distributed across the team.
In all four team concepts, the mission commander was heavily tasked with monitoring and coordinating crew and with liaising with external agencies.	The mission commander's housekeeping duties may distract him or her from the primary responsibility of understanding the emerging tactical situation and making effective decisions. Thus in all four team concepts, the purpose-related functions of portraying the tactical situation and asset coordination, and the priorities and values of maintaining a knowledge edge and a geostrategic advantage, may be compromised.	For reasonably complex scenarios, a better team design may be to introduce a deputy mission commander to take on the roles of supervisor and coordinator.

team design, we would have had to base the AEW&C team design on older-generation systems such as AWACS or E2C. As a result, the AEW&C team design may have promoted undesirable work patterns from the older systems or it may not have tapped into potentially effective work patterns offered by the new technology.

The CWA-based technique for team design also allowed us to describe the work requirements of AEW&C in terms that captured a wide variety of potential work patterns. If we had used conventional approaches for team design, we would have specified the work requirements of AEW&C in terms of stable sets of tasks or work procedures. However, given that workers develop new ways of working as they gain experience with new technology and when dealing with novel or unpredictable contingencies, a specification of AEW&C tasks and work procedures would have been incomplete. Consequently, the resulting AEW&C team design might not have been well suited to work requirements that could not be specified in advance.

The CWA-based technique for team design relies on judgments by subject matter experts and analysts of the impact of the distribution of work problems on the work domain and, subsequently, of the requirements for a new team design. At the very early stages of system development there appears to be no better alternative. Later during system development, when mockups, prototypes, or simulations of the future environment become available, the team design should be evaluated empirically. Dekker and Woods (1999), for example, described how they conducted an empirical evaluation of an envisioned air traffic control system using airspace maps depicting future airspace layouts, static representations of future radar displays, and future procedures.

In this project it was not practical to evaluate how the recommendations for AEW&C team design using the CWA-based technique would differ from those generated using other approaches. First, we were faced with the same practical constraints as exist in many other industry projects, such as time and resource limitations and the availability of subject matter experts. Second, there were constraints that were specific to this project. For example, in order to experiment with descriptive techniques for team design, we would require access to existing, older-generation systems such as AWACS or E2C, which are not available in Australia.

CONCLUSION

In this paper we have presented a CWA-based technique for team design and have demonstrated that it provides a useful and feasible approach for designing teams for first-of-a-kind, complex systems during the early stages of development. We acknowledge that we have not yet verified that the CWA-based technique will lead to effective team designs for these kinds of systems. However, because of the same practical constraints that we had on this project, techniques that are used in industry are rarely evaluated in a formal way (Czaja, 1997). Rather, the criteria that are typically used include the feasibility of the technique, its usefulness, and its ability to influence practice (Rouse & Cody, 1986; Vicente, 1999; Whitefield, Wilson, & Dowell, 1991). The CWA-based technique for team design fulfilled these criteria in the case of AEW&C. We hope the adoption of this technique by others will lead to further tests against these criteria. Moreover, with time the fields of application will function as natural laboratories (Woods, 1998), and we will determine whether the CWA-based technique leads to effective team designs in operational settings.

Meanwhile, the development of many other first-of-a-kind, complex systems such as AEW&C may proceed in the absence of empirical data for any of the techniques for team design. On the basis of the arguments presented in this paper, it seems reasonable to expect that for first-of-a-kind, complex systems at the early stages of development, the CWA-based technique for team design will offer better results than basing team design purely on intuition, informal analyses, or conventional techniques for team design.

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Neelam Naikar obtained her Ph.D. in psychology in 1996 from the University of Aukland, New Zealand. She is a senior research scientist at the Defence Science and Technology Organisation (DSTO) in Melbourne, Australia.

Brett Pearce obtained a G. Dip. in software development from RMIT University, Melbourne, in 2001. He is a human factors researcher at DSTO.

Dominic Drumm obtained a B.Sc. in physics from the National University of Ireland in 1962. He is a human factors researcher at DSTO.

Penelope M. Sanderson is professor of cognitive engineering, leader of the Cognitive Engineering Research Group, and director of the Usability Laboratory at the University of Queensland. She received her Ph.D. in engineering psychology at the University of Toronto in 1985.

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