Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
International Journal of Industrial Ergonomics 36 (2006) 423–438
International Journal of INDUSTRIAL ERGONOMICS
www.elsevier.com/locate/ergon

Beyond interface design: Further applications of cognitive work analysis

Neelam Naikar*

Defence Science and Technology Organisation, PO Box 4331, Melbourne, VIC 3001, Australia

Abstract

Cognitive work analysis (CWA) is gaining momentum as an approach for the analysis, design, and evaluation of complex sociotechnical systems. The majority of applications of CWA have focussed on interface design but in this paper we demonstrate that CWA can also be used for a variety of other applications. These applications include the use of CWA to: identify training needs and training-system requirements; evaluate alternative system design proposals; develop team designs; and identify training strategies for managing human error. By discussing how CWA has been employed in these areas for the Australian Department of Defence, this paper demonstrates that CWA can consistently produce feasible and useful outcomes on industry projects for applications other than interface design.

Relevance to industry

This paper demonstrates the application of CWA to a variety of industry projects for analysing training needs and training-system requirements, evaluating alternative system design proposals, developing team designs, and identifying training strategies to manage human error.
© 2006 Elsevier B.V. All rights reserved.

Keywords: Cognitive work analysis; Work domain analysis; Control task analysis; System design; System development; System acquisition; Task analysis

1. Introduction

Cognitive work analysis (CWA) (Rasmussen et al., 1994; Vicente, 1999) is gaining momentum as an approach for the analysis, design, and evaluation of complex sociotechnical systems (e.g., Vicente, 1992a, b; Rasmussen, 1998; Reising and Sanderson, 1998; Dinadis and Vicente, 1999; Bisantz et al., 2003; Burns, 2000; Burns et al., 2000, 2004; Burns and Hajdukiewicz, 2004; Leveson, 2000; Gualtieri et al., 2001; Linegang and Lintern, 2003). The majority of applications of CWA; however, have focussed on interface design. In addition, the majority of applications of CWA do not have demonstrated outcomes on industry projects.

In this paper, we review applications of CWA to areas other than interface design on industry projects. These applications, which were undertaken for the Australian Department of Defence, include: the analysis of training needs and training-system requirements for the acquisition of a training system for F/A-18 fighter aircraft (Naikar and Sanderson, 1999); the evaluation of alternative design proposals for the acquisition of a new Airborne Early Warning and Control (AEW&C) system (Naikar and Sanderson, 2001); the development of a team design for the AEW&C system (Naikar et al., 2003); and the development of training strategies to manage human error for F-111 strike aircraft (Naikar and Saunders, 2003). Although we have reported these applications of CWA previously,[1] these publications were focussed on individual projects. By reviewing the outcomes of all of these applications of CWA, this paper provides a basis for assessing the overall usefulness and feasibility of CWA on industry projects in areas other than interface design. We start by providing a brief introduction to CWA.

*Tel.: +61 3 9626 7940; fax: +61 3 9626 7084.
E-mail address: neelam.naikar@dsto.defence.gov.au.

[1]Readers may notice some small differences between this paper and our original papers, such as differences in terminology; these differences reflect our latest thinking on CWA.

0169-8141/$ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.ergon.2006.01.006

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). Descriptive approaches to work analysis seek to understand how work is 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., Seamster et al., 1997; Zsambok and Klein, 1997; Schraagen et al., 2000).

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). This approach recognises that many tasks in complex sociotechnical systems are discretionary and that workers have a great variety of options with respect to what to do and when and how. In addition, the CWA approach recognises that the main role of workers in complex sociotechnical systems is to deal with unanticipated events, which are situations that pose the greatest threat to system performance and safety. Therefore, rather than focussing on how work should be done or how work is done under particular conditions or in particular situations, CWA focuses on the constraints or boundaries 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. As there are several kinds of constraints or boundaries that can shape workers' behaviour, several dimensions of analysis are necessary.

Table 1 shows that CWA consists of several phases of analysis for identifying the different kinds of constraints or boundaries on workers' behaviour; the phases of CWA are labelled slightly differently by Vicente (1999) and Rasmussen et al. (1994). In this paper, we focus on applications of CWA that are based on work domain analysis (WDA) and control task analysis (ConTA). These phases of CWA are shown in italics in the table.

2.1. Work domain analysis

WDA identifies the constraints on workers' behaviour that are imposed by the purposive and physical context, or problem space, in which workers operate. The abstraction-decomposition space, which is the main modelling tool for WDA, structures the problem space of workers along two orthogonal dimensions—the abstraction dimension or hierarchy and the decomposition dimension or hierarchy. The abstraction hierarchy models the purposive and physical problem space of workers in terms of different levels of abstraction or conceptual viewpoints whereas the decomposition hierarchy models the purposive and physical problem space of workers at different levels of detail. The applications of WDA that we discuss in this paper emphasise the abstraction hierarchy.

Fig. 1 shows a generic abstraction hierarchy with five levels of abstraction. The top three levels of abstraction, which represent the purposive context in which workers operate, describe: the high-level aims or objectives of the

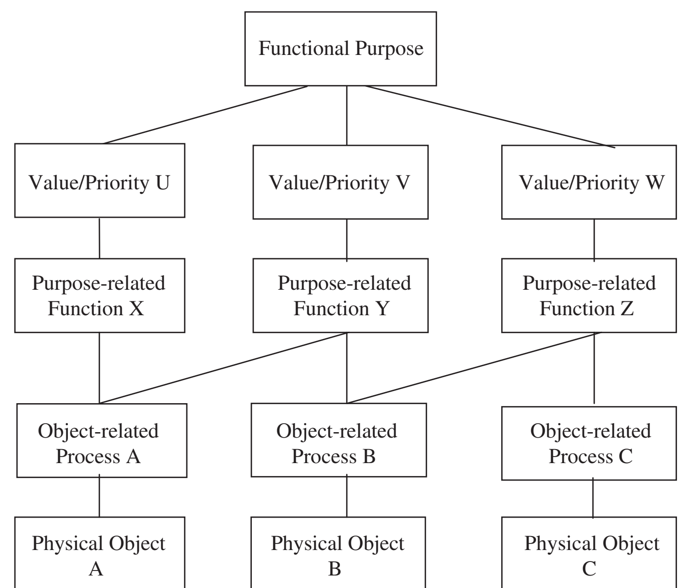

Fig. 1. A generic abstraction hierarchy with five levels of abstraction and means-ends relations between the different levels of abstraction.

Table 1
The phases of CWA as they are labelled by Vicente (1999) and Rasmussen et al. (1994) and the types of constraints or boundaries that are the focus of each phase of analysis

Vicente (1999)	Rasmussen et al. (1994)	Types of constraints or boundaries
Work domain analysis	Work domain analysis	Purposes, values and priorities, functions, and physical resources.
Control task analysis	Activity analysis in work domain terms and activity analysis in decision making terms	Activity in terms of work situations, work functions, and control tasks.
Strategies analysis	Activity analysis in terms of mental strategies	Strategies for carrying out activity.
Social organisation and cooperation analysis	Analysis of the work organisation	Distribution of work including allocation of work to individuals; organisation of individuals into teams; and communication requirements.
Worker competencies analysis	Analysis of system users	Perceptual and cognitive capabilities of workers

work system (functional purposes); the criteria for measuring whether the work system is progressing towards its functional purposes (values and priority measures); and the functions of the work system that are necessary for achieving the functional purposes (purpose-related functions). The bottom two levels of abstraction, which represent the physical context in which workers operate, describe: the functional capabilities and limitations of physical objects in the work system (object-related processes); and the physical objects in the work system (physical objects).

The links between the different levels of the abstraction hierarchy are means-ends or how-why relations. Links from a target node to lower levels of abstraction indicate *how* that node is engineered or operationalised (means). Conversely, links from a target node to higher levels of abstraction indicate *why* that node exists (ends).

2.2. Control task analysis

ConTA identifies the constraints on workers' behaviour that are imposed by the activity that is necessary in a work domain for achieving the purposes, values and priorities, and functions of a work domain with a given set of physical resources. Traditional approaches to work or task analysis typically decompose activity into sequences of tasks or actions. In ConTA, activity is characterised, first, as a set of recurring work situations to deal with and/or a set of work functions to perform and, second, as the set of control tasks that are required for each work situation and/or work function (Naikar et al., in press).

Fig. 2 shows a generic contextual activity template for representing activity in work systems that are characterised by both work situations and work functions (Naikar et al., in press). In this template, work situations are shown along the horizontal axis and 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.

Once activity has been characterised as a set of work situations and/or work functions, the decision ladder template (Rasmussen et al., 1994; Vicente, 1999) can be used to represent the set of control tasks for each work situation and/or work function. The boxes in the decision ladder template (Fig. 3) represent information-processing activities whereas the ovals represent the states of knowledge that are the results or outputs of those activities. The arrows in the centre of the decision ladder indicate shortcuts from one part of the decision ladder to another; only some examples of shortcuts are shown in Fig. 3.

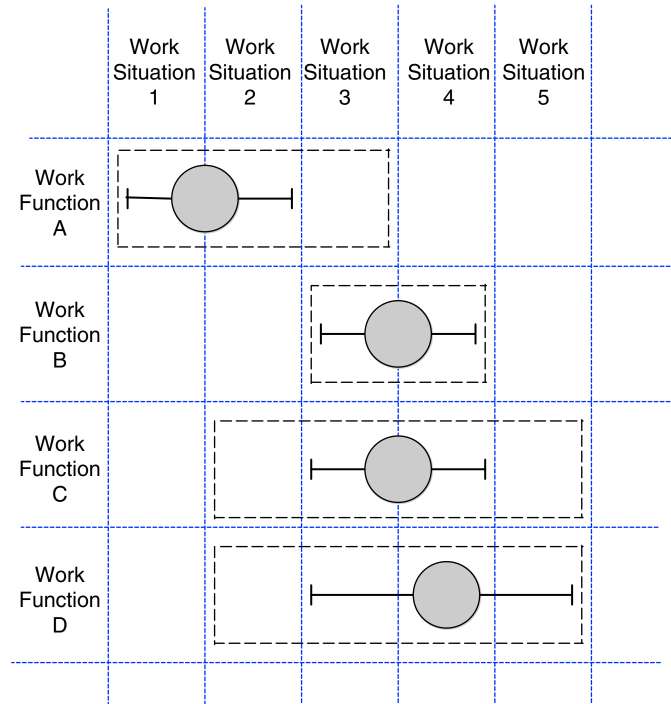

Fig. 2. A generic contextual activity template for representing activity in work systems that are characterised by both work situations and work functions.

3. Training needs analysis and training-system requirements

This project involved the use of WDA, the first phase of CWA, to identify training needs and training-system requirements. Many organisations tend to work under the assumption that simply purchasing expensive, high-fidelity training devices will reduce training costs, increase levels of skill in the workforce, and reduce the risk of accidents on the job (Lintern and Naikar, 1998). For two main reasons, these expectations have not always been realised. First, limited attention has been paid to the analysis of training needs in these organisations. Second, even if a training needs analysis is conducted, limited attention has been paid to the systematic specification of training-system requirements that are necessary for satisfying the organisation's training needs.

Standard techniques for training needs analysis focus on identifying a taxonomy of tasks or sequences of tasks that are required for performing various jobs or roles in an organisation (Department of the Air Force, 1993). These techniques can be used to develop detailed procedures for training workers to deal with routine or anticipated events. Given that much of the work in many organisations is routine or familiar to workers, standard techniques for training needs analysis are useful for developing training systems that will allow workers to practice procedures for dealing with a large proportion of the situations that they will encounter.

The greatest threats to system performance and safety, however, are posed by situations that have not been

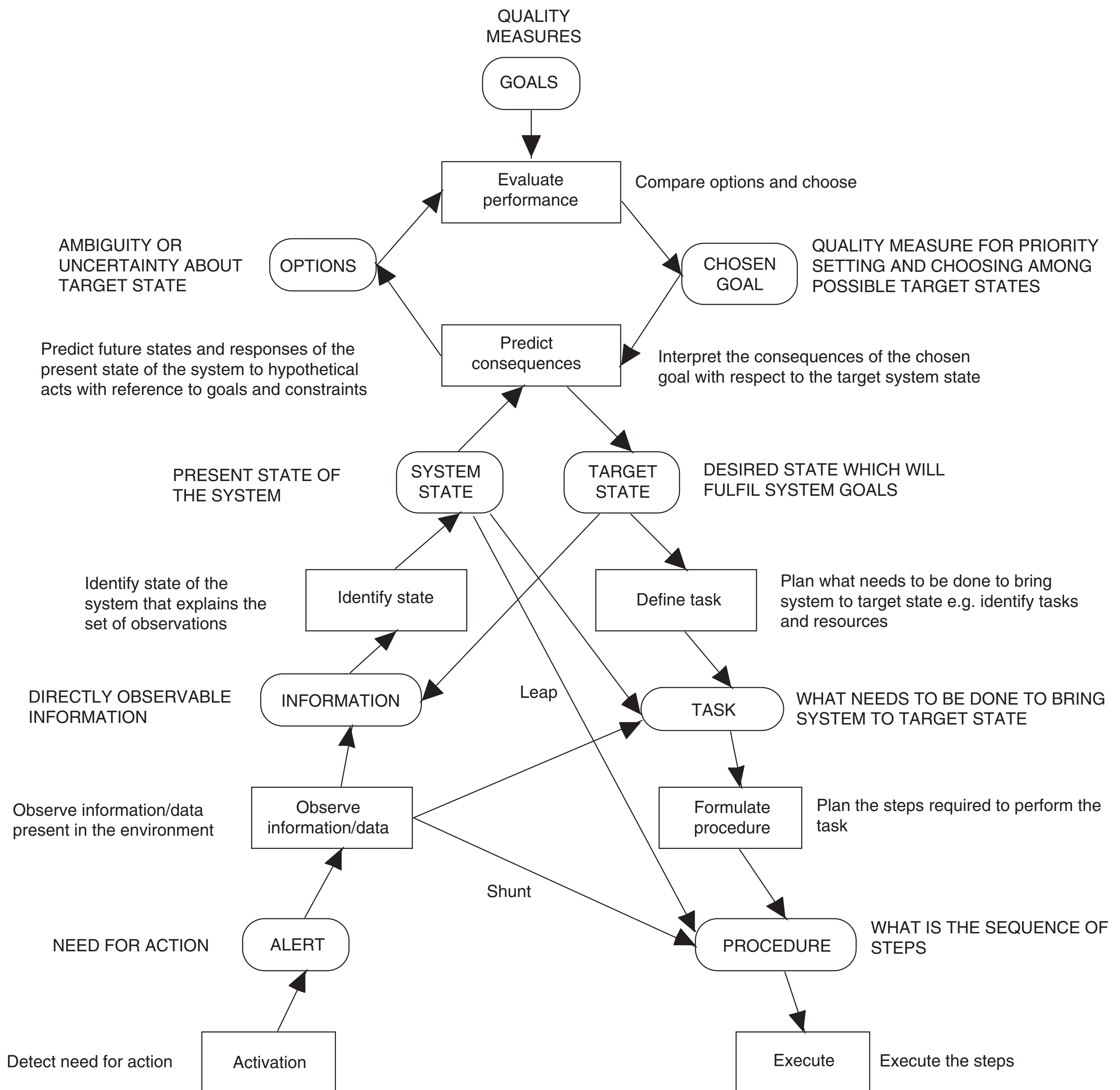

Fig. 3. A generic decision ladder template for representing the set of control tasks for each work situation and/or work function.

encountered or anticipated by workers or by systems analysts and engineers (Vicente, 1999). In these situations, workers cannot always rely on procedures that have been developed a priori for dealing with routine or anticipated events. Instead, creative problem-solving skills and new patterns of behaviour are often required to prevent the system from failing. To prepare workers for dealing with these kinds of situations effectively, training-system design must provide opportunities to practise adaptive behaviour.

By identifying the boundaries or constraints within which workers operate, WDA provides a framework for designing training systems that will support adaptive behaviour (Naikar and Sanderson, 1999; Lintern and Naikar, 2000). Within the boundaries defined by the purposes, values and priorities, functions, and physical resources of a work domain, workers have many options or possibilities for action in the work domain. Therefore, if the design of a training system, such as a simulator, is based on WDA, the simulator will offer possibilities for action that are parallel to those available to workers in the real world. Such a simulator, with means-ends fidelity, can be used for training workers to explore the alternative

Table 2
WDA provides a framework for identifying training needs and training-system requirements

	Training needs	Training-system requirements
Functional purposes	Training objectives: the ultimate purposes or high-level objectives that workers must be able to achieve as a result of their training.	Design objectives: the training system must be capable of satisfying the training objectives of the work domain.
Values and priority Measures	Measures of performance: the specific criteria that workers must be able to satisfy as a result of their training.	Data collection: the training system must be capable of collecting data relating to the measures of performance in the work domain.
Purpose-related functions	Basic training functions: the fundamental functions that workers must be competent in executing and coordinating as a result of their training.	Scenario generation: the training system must be capable of generating scenarios for training the fundamental functions of the work domain.
Object-related processes	Physical functions: the functionality of physical devices that workers must be able to exploit and the environmental conditions under which workers must be able to operate as a result of their training.	Physical functionality: the training system must be capable of simulating the functionality of physical devices and significant environmental conditions in the work domain.
Physical objects	Physical objects: the functionally relevant properties of physical devices and significant features of the environment that workers must be able to recognise as a result of their training.	Physical attributes: the training system must be capable of recreating the functionally relevant properties of physical devices and significant features of the environment in the work domain.

means for achieving multiple system ends whilst remaining within the constraints of the work domain.

Table 2 shows that each level of the abstraction hierarchy can be used to derive particular kinds of training needs and training-system requirements. In terms of training needs, WDA can be used to derive: the training objectives of a work system or organisation; the measures of performance or criteria that trainees must satisfy; the fundamental functions that trainees must have competence in; the functionality of physical devices that trainees must be able to exploit and the environmental conditions under which trainees must be able to operate; and the functionally relevant properties of physical devices and significant environmental features that trainees must be able to recognise. In terms of training-system requirements, WDA can be used to derive: the design objectives of a training system; the data collection capabilities of a training system; the scenario generation capabilities of a training system; the functionality of physical devices and the environmental conditions that the training system must be able to simulate; and the physical attributes that the training system must be able to recreate.

The WDA framework for identifying training needs and training-system requirements was used to support the acquisition of a training system for F/A-18 fighter aircraft in the Royal Australian Air Force as part of an upgrade program (Naikar and Sanderson, 1999). A standard training needs analysis based on the identification of tasks was also conducted. To conduct the F/A-18 WDA, we analysed various strategic, tactical, training, and flight manuals relating to F/A-18 and we also relied on input from F/A-18 domain experts. Table 3 shows a sample of the F/A-18 abstraction hierarchy and the kinds of training needs and training-system requirements that were derived from each level of abstraction.

The training needs and training-system requirements for F/A-18 that were identified by WDA were released in the request for tender documentation for the acquisition of a training system for F/A-18. Hence, to win the contract for the provision of an F/A-18 training system to the Australian Department of Defence, the proposals submitted by training-system manufacturers had to address whether the training systems they were offering would fulfil the training needs and training-system requirements for F/A-18 as identified by WDA. Compared with many previous acquisitions of training systems by the Australian Department of Defence, the training-system requirements identified by WDA emphasised functionality over technical specifications because the requirements were derived directly from the functional structure of the F/A-18 work domain itself. In addition, the training-system requirements identified by WDA were considerably more comprehensive than those for previous acquisitions because the requirements were derived from multiple levels of analysis of the F/A-18 work domain (as opposed to simply from an analysis of F/A-18 tasks). Finally, the WDA approach bridged the gap between the analysis of training needs and the identification of training-system requirements because each category of training needs was directly related to specific kinds of training-system requirements.

4. Evaluation of system design proposals

As well as identifying requirements for the acquisition of a new system, WDA also provides a framework for evaluating the design proposals that are submitted by competing manufacturers to win the contract for the

Table 3
A sample of the F/A-18 abstraction hierarchy and the kinds of training needs and training-system requirements that were derived from each level of abstraction

F/A-18 Abstraction hierarchy	F/A-18 Training needs	F/A-18 Training-system requirements
Functional purposes: to ensure security of sovereign airspace, to maintain the initiative for offensive action	Training objectives: fighter pilots must be able to ensure security of sovereign airspace and to maintain the initiative for offensive action as a result of their training.	Design objectives: the F/A-18 training system must be capable of training fighter pilots to ensure security of sovereign airspace and to maintain the initiative for offensive action.
Values and priority measures: minimise collateral damage, reduction in enemy combat effectiveness	Measures of performance: fighter pilots must be able to minimise collateral damage and reduce enemy combat effectiveness as a result of their training.	Data collection: the F/A-18 training system must be capable of collecting data relating to whether fighter pilots were able to minimise collateral damage and reduce enemy combat effectiveness in a training scenario.
Purpose-related functions: flight, evaluation of tactical situation, weapons delivery to air and surface threats	Basic training functions: fighter pilots must be capable of executing and coordinating the functions of flight, evaluation of tactical situation, and weapons delivery to air and surface threats as a result of their training.	Scenario generation: the F/A-18 training system must be capable of generating scenarios for training fighter pilots to execute and coordinate the functions of flight, evaluation of tactical situation, and weapons delivery to air and surface threats.
Object-related processes: supersonic cruise, levels of hostility, weather	Physical functions: fighter pilots must be able to exploit the supersonic cruise capability of the F/A-18 aircraft and operate under different levels of hostility and weather conditions as a result of their training.	Physical functionality: the F/A-18 training system must be capable of simulating the supersonic cruise capability of the F/A-18 aircraft and different levels of hostility and weather conditions.
Physical objects: VHF/UHF/HF radio channels, air and surface threats	Physical objects: fighter pilots must be able to recognise the functionally relevant properties of VHF/UHF/HF radio channels and air and surface threats as a result of their training.	Physical attributes: the F/A-18 training system must be capable of recreating the functionally relevant properties of VHF/UHF/HF radio channels and air and surface threats.

development of a new system (Naikar and Sanderson, 2001). This stage of the acquisition cycle is referred to as tender evaluation in the United Kingdom and Australia and as source selection in the United States of America. This is an important stage of acquisition because following the selection of a particular design proposal, the buyer gets locked into that design concept and further evaluation is focussed on modifying or refining the chosen design.

Complex sociotechnical systems have many special characteristics that place unique requirements on the evaluation of designs. First, complex sociotechnical systems consist of a technical component that serves as a resource for fulfilling the functions and objectives of a broader work context. A framework for evaluation must therefore not only be concerned with the technical soundness of a proposed design but also whether the technical solution fulfils the requirements of the broader work context. Second, complex sociotechnical systems are required to deal with a great many events, including novel or unanticipated contingencies, which pose a significant threat to its performance and safety (Vicente, 1999). A framework for evaluation must therefore promote an understanding of whether a proposed design will satisfy the requirements of a work system in a large variety of situations, including novel or unanticipated situations.

Standard approaches to evaluation, which involve a technical evaluation and an operational evaluation, only partially fulfil the requirements for evaluating designs for complex sociotechnical systems (Naikar and Sanderson, 2001). The technical evaluation focuses on evaluating the various physical subsystems which make up the technical component of a proposed design against a set of pre-specified technical performance criteria (the physical subsystems of an aircraft, for example, include its radar, communications, and navigation subsystems). This step provides a detailed understanding of the technical soundness of a proposed design. However, it does not promote an understanding of whether the technical solution will fulfil the requirements of the relevant work context.

The operational evaluation focuses on evaluating the performance of the technical solution of a proposed design in a range of mission scenarios. This step promotes a detailed understanding of how a proposed design will deal with the work requirements of typical mission scenarios. However, because of logistical difficulties, the evaluation is usually limited to a small number of scenarios relative to the total number of possibilities. In addition, the scenarios that are considered during evaluation are limited to those that are known or can be anticipated by domain experts. The operational evaluation therefore does not promote an understanding of whether the proposed designs will fulfil the requirements of a broad range of situations, including novel or unanticipated situations.

In contrast to standard techniques for evaluation, WDA provides a framework for evaluation that is event-independent. Instead of evaluating the performance of alternative designs in specific scenarios, WDA focuses on evaluating the designs against constraints or boundary

conditions that are relevant to a broad range of situations, including situations that cannot be specified up front. Using this framework for evaluation, the physical-device solutions (physical objects and object-related processes) of proposed designs can be evaluated in terms of how well they fulfil the higher level functions and objectives of a work domain (purpose-related functions, values and priorities, functional purposes). Fig. 1 illustrates that the technical solutions relating to Physical Object B and Object-related Process B, for instance, can be evaluated in terms of how well they support Purpose-related Functions Y and Z. The effect on the purpose-related functions can then be evaluated against Values and Priority Measures V and W and the functional purpose of the work domain.

The WDA framework for evaluation was used to evaluate the alternative design proposals submitted by three aircraft manufacturers (hereby referred to as Companies A, B, and C) for the provision of an AEW&C system to the Australian Department of Defence (Naikar and Sanderson, 2001). The technical evaluation and operational evaluation techniques were also used on this project. To conduct the AEW&C WDA, we analysed various strategic documents as well as engineering documents of requirements and specifications and we also relied on input from AEW&C domain experts.

Fig. 4 shows a sample of the AEW&C abstraction hierarchy to illustrate that this framework can be used to trace the impact of physical-device solutions on the entire work context. In particular, the figure shows that if deficiencies in the design of the radio voice links compromise the ability to exchange information and communicate, then the ability to establish, update, and disseminate the tactical picture, and to exercise control over friendly assets will also be compromised. However, if the deficiency results in reduced electronic and radio transmissions from the platform, then the presence of the platform will be communicated less broadly, which will help to preserve the platform, sensors, and information systems from attack.

The process for using the WDA framework for evaluation took advantage of the structure of the evaluation team that had been set up for the AEW&C technical evaluation. This team was divided into subgroups that were responsible for evaluating the designs of particular physical devices of AEW&C (e.g., radar subgroup, communications subgroup). For the technical evaluation, each subgroup rated whether the physical devices for which they were responsible exceeded, complied with, or were deficient relative to pre-specified technical performance requirements. Subsequently, each subgroup evaluated the results of the technical evaluation against the purpose-related functions of AEW&C. After the subgroups had completed their reports, the head of the evaluation team, assisted by the leaders of the subgroups, summarised the overall impact (across physical devices or subgroups) on the purpose-related functions of AEW&C. The results at the purpose-related functions level were then evaluated in terms of the impact on the values and priorities and the functional purposes of AEW&C. After this process was completed for each design proposal, the three design proposals were compared and ranked in terms of how well they supported each of the purpose-related functions, values and priorities, and functional purposes of AEW&C.

Compared with standard techniques for evaluation, the WDA approach provided a framework for integrating the results of the technical evaluation across all of the physical devices of the AEW&C system, which made it possible to select the best overall design. Without WDA, it would have been difficult to select the best overall design because the radar subgroup, for example, may have ranked Company A ahead of the other two proposals whereas

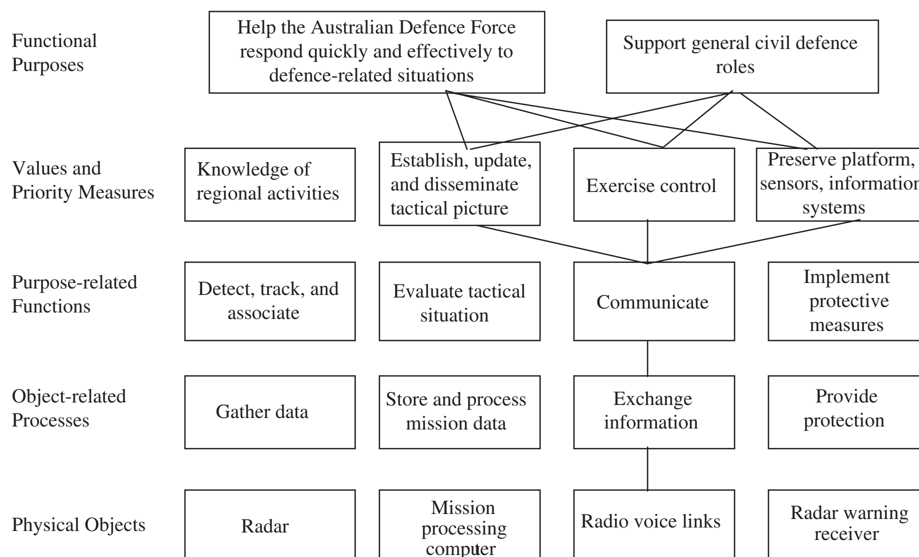

Fig. 4. A sample of the abstraction hierarchy for AEW&C.

the communications subgroup may have ranked Company B ahead of the other two proposals and the navigation subgroup may have ranked Company C ahead of the other two proposals. With WDA, all of the physical-device solutions could be compared and ranked on a common set of functional criteria. The WDA framework also shifted the focus of evaluation from technical properties to the work requirements of AEW&C. Consequently, the results of the evaluation could be expressed in terms of military utility. Finally, the WDA framework provided an event-independent approach to evaluation that promoted an understanding of how the proposed designs for AEW&C would perform in a broad range of situations, including situations that cannot be specified up front.

5. Team design

A third application for which we have used CWA is to design teams for future, first-of-a-kind systems. First-of-a-kind systems are systems that have no close existing analogues, usually because technological advances have led to vastly improved functionality compared to older systems. As a result, the behaviour of workers in the future, first-of-a-kind system cannot be inferred entirely from that of workers in existing systems. In addition, at the early stages of system development, detailed information about the behaviour of workers in the future system is also unavailable. Yet it is desirable to develop a team design as early as possible because as system development proceeds, the technical solution starts to get 'locked in' and the team design is more likely to be constrained by the technical solution.

Standard techniques for team design (e.g., Hackman and Oldham, 1980; Davis and Wacker, 1982; Dubrovsky and Piscoppel, 1991) have been useful for designing teams for existing systems. However, for two main reasons, these techniques cannot readily be applied to first-of-a-kind, future systems during the early stages of development (Naikar et al., 2003). First, some of the techniques are based on descriptive approaches to work analysis, which rely on observing and analysing workers' behaviour in their actual work settings. However, at the early stages of system development, the proposed work system does not exist in a physical form. Second, other techniques for team design are based on normative approaches to work analysis, which describe work requirements in terms of stable sets of tasks or work procedures. However, workers in complex sociotechnical systems will often develop novel ways of working as they gain experience with a new system so it is difficult to specify the full set of work procedures ahead of a system being put into operation. Furthermore, it is difficult to specify stable sets of tasks or work procedures for dynamic or unanticipated events.

CWA, in contrast, offers a framework for designing teams for first-of-a-kind, future systems during the early stages of its development because it focuses on the constraints or boundary conditions that shape workers' behaviour in the first place. These constraints can capture a large variety of work patterns or trajectories of workers' behaviour, including those that cannot be specified up front. In addition, the analysis of constraints can take place in the absence of a physical work system.

The CWA-based approach to team design that we have developed consists of three main steps (Naikar et al., 2003). The first step involves conducting a WDA to identify the purposes, values and priorities, functions, and physical resources of a new system. The second step involves conducting a ConTA to identify the work situations and work functions of the new system. The third step involves a table-top analysis that utilises the WDA and ConTA to explore the feasibility of alternative team concepts for the new system. This technique was used to design a team for the AEW&C system at the early stages of its development (Naikar et al., 2003). Since we have already described the WDA for AEW&C, we will focus on the ConTA and table-top analysis.

Fig. 5 shows the AEW&C ConTA, or contextual activity template, which highlights the recurring work situations that AEW&C workers will need to deal with and the recurring work functions that AEWC workers will need to perform. The work situations, which are shown along the horizontal axis, are the different phases of a mission. The work functions are shown in the circles. In a separate document, we defined each work function in terms of the problem that is presented to workers. For example, for manage crew, the problem is to distribute responsibilities, assets, and other resources amongst crew in order to support the aims of a mission under changing tactical and environmental conditions. For this project, we did not identify the control tasks that are required for each work situation and/or work function, which is the second part of ConTA (see the discussion in Section 2.2).

The AEW&C table-top analysis consisted of five sub-steps. The first sub-step involved identifying the team-design variables that the AEW&C System Program Office wanted to examine and the set of values for each variable that were plausible for AEW&C. Fig. 6 shows that the team-design variables that we identified included: the size of the team, the number of levels of hierarchy in the team, the number of subteams, and whether team members should have dedicated roles and responsibilities or whether they should be multi-skilled. Fig. 6 also shows that for the variable of team size, for example, values between 6 and 10 were judged to be plausible for AEW&C. Each pathway in Fig. 6, which consists of different combinations of values across the four team-design variables, specifies the alternative team concepts to explore with the table-top analysis. The first pathway, for instance, specifies a team concept with 6 team members, two levels of hierarchy, no subteams, and team members with dedicated roles and responsibilities.

The second sub-step involved working with Australian Defence Force personnel to develop air defense scenarios that were representative of the kinds of missions in which

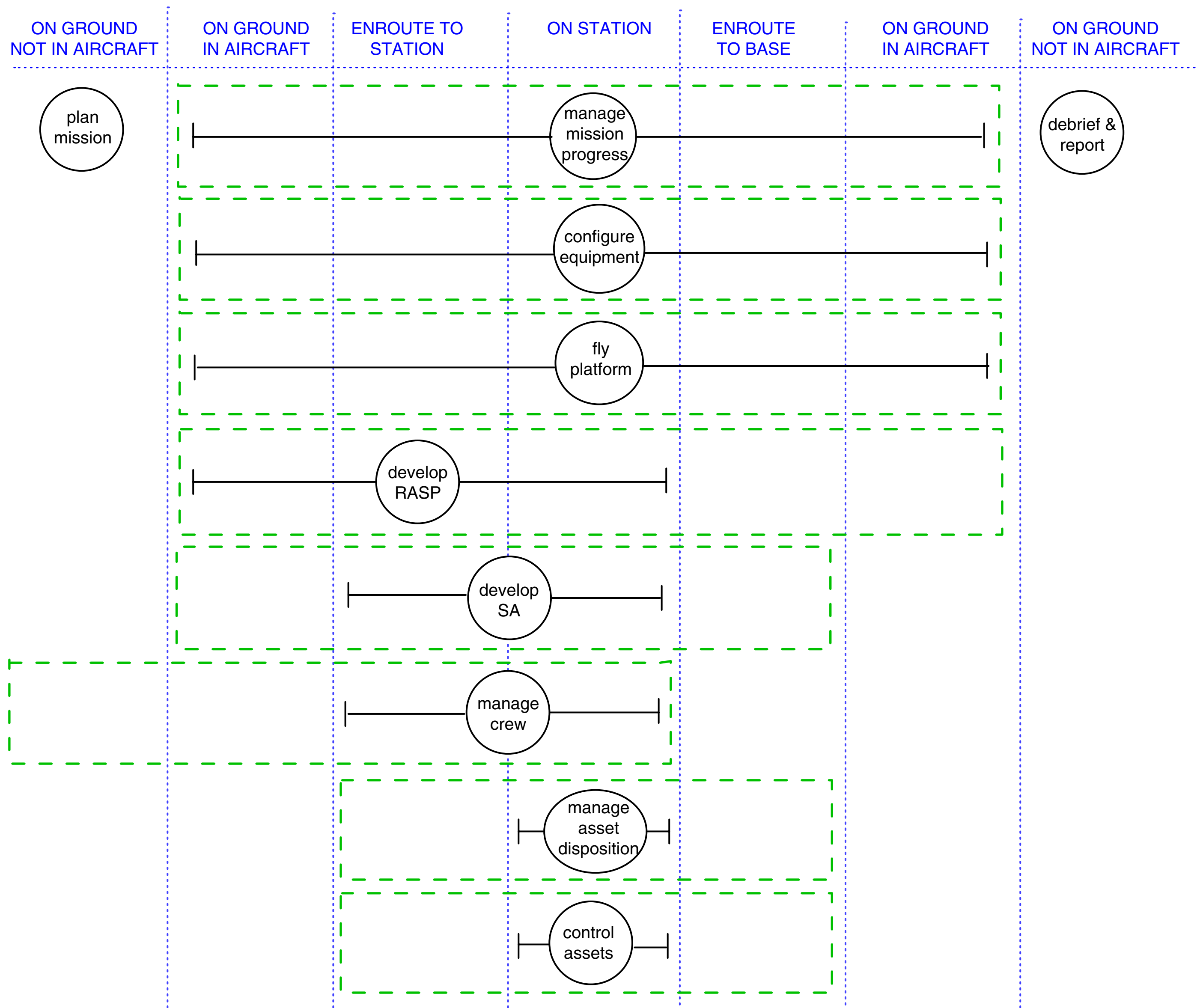

Fig. 5. The contextual activity template for AEW&C illustrating its work situations and work functions.

AEW&C may be involved. We developed scenarios that were considered both routine and exceptional for AEW&C and we identified the critical events in each scenario (e.g., strike package enters no fly zone, hostile firing of friendly ships).

In the third sub-step, we worked with military experts who had a thorough knowledge of the AEW&C system specification to explore how the scenarios would be handled with the alternative team concepts in Fig. 6. Specifically, we identified the work demands associated with the critical events in the scenarios and we explored how these work demands would be distributed across team members given the alternative team concepts.

In the fourth sub-step, we translated the work demands that the military experts had described into work functions from the AEW&C ConTA. By focusing on work functions, rather than on scenario-specific work demands, it became possible to compare the alternative team concepts across different scenarios. In addition, the work functions allowed us to express the distribution of work across team members in terms of a set of constraints that can accommodate a large variety of sequences of tasks or trajectories of behaviour. In the first instance, though, it was necessary to conduct the table-top analysis in terms of scenarios and scenario-specific work demands because this was the most suitable approach for eliciting the necessary information from military experts; military experts are used to thinking about their work in terms of scenarios and the work demands or activities associated with those scenarios rather than in terms of work functions.

To illustrate the kinds of representations that resulted from the fourth sub-step, Fig. 7 shows the distribution of work functions to team members for the same time segment in a scenario but for two different team concepts.

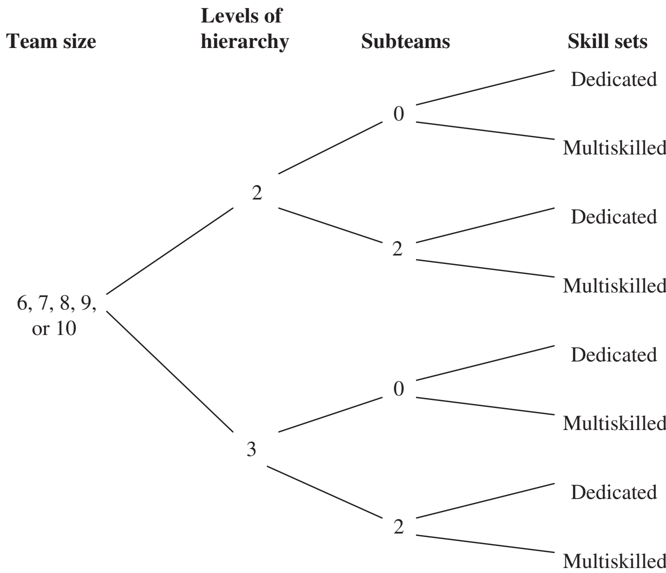

Fig. 6. The team-design variables for AEW&C (team size, levels of hierarchy, subteams, skills sets) and the set of plausible values for each variable.

The main difference between the two team concepts is the size of the team; the team concept to the left of the figure has ten team members whereas the team concept to the right of the figure has six team members. In these representations, the critical events in the scenario are described in the columns (e.g., dividing ES sectors, identifying tracks of interest, control of P3); the roles of each of the team members are described in rows (e.g., Mission Commander, Fighter Controller); the work functions that the team members are allocated are described in the circles (e.g., configure equipment, control assets); and the communication and coordination requirements associated with the allocation of work functions to team members are shown with arrows (the arrows are numbered and described at the bottom of the figure). The rows that are shaded in the six-person team concept represent those individuals in the ten-person team who are not available in the six-person team. The bold circles represent the added responsibilities of team members in the six-person team, given the reduction in team size from ten to six; thus, these are work functions with which the corresponding team members in the ten-person team did not have to deal.

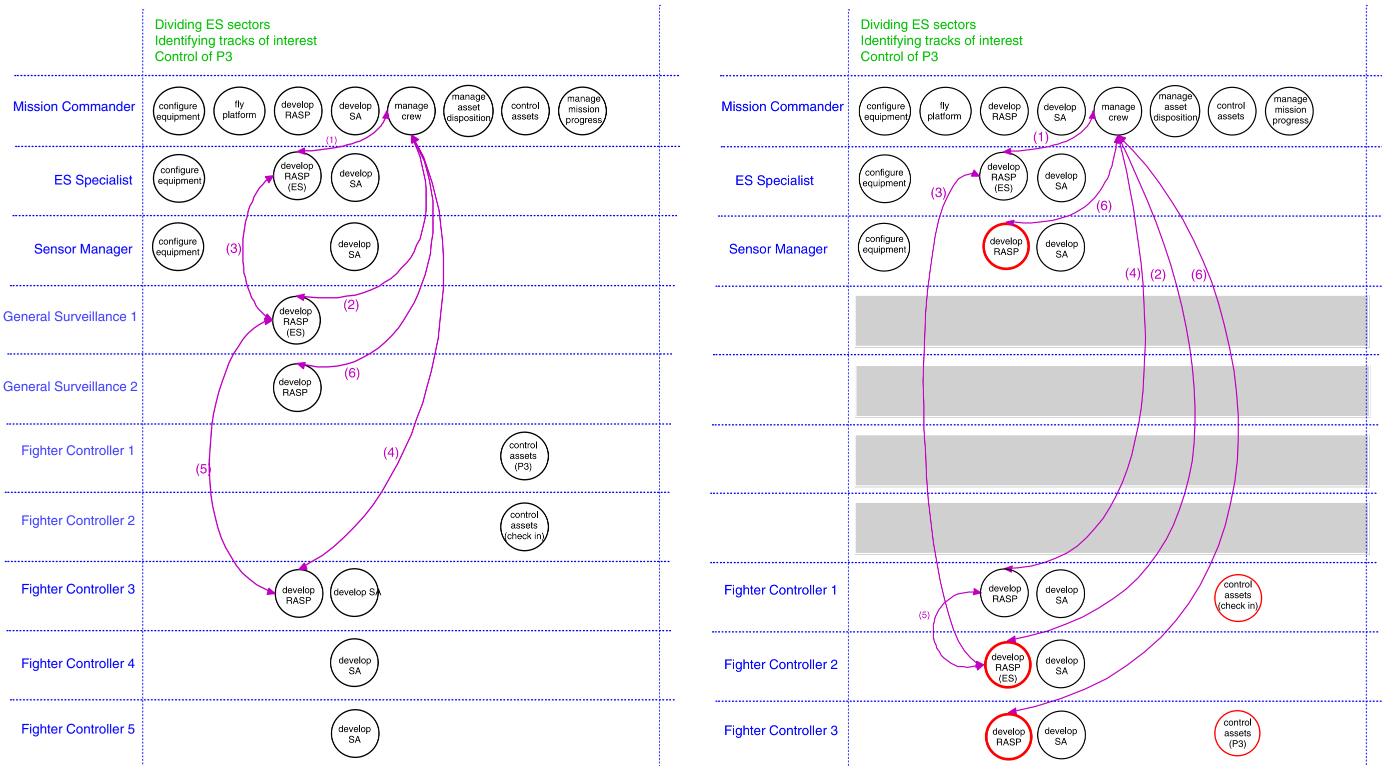

Fig. 7. The distribution of AEW&C work functions to team members for the same time segment in a scenario but for two different team concepts.

In the final sub-step of the table-top analysis, we evaluated the different team concepts and generated requirements for a new team design. First, we identified differences in the distribution of work functions for the alternative team concepts and/or recurring patterns in the distribution of work functions for the alternative team concepts. One of the differences in the distribution of work functions that we observed, for example, was between the six-person, dedicated team and the six-person, multi-skilled team (both of these team concepts had two levels of hierarchy and no sub-teams). In the dedicated team, at least one team member was always devoted to general maintenance of the tactical picture throughout the scenario. However, in the multi-skilled team, individuals who were responsible for general maintenance of the tactical picture were also controlling and managing assets at critical points in the scenario.

Having identified differences and recurring patterns in the distribution of work functions for the alternative team concepts, we then evaluated the alternative team concepts in terms of how well these different and/or recurring patterns of activity supported the purposes, values and priorities, and functions of AEW&C as well as how effectively the physical resources of the work domain were shared; these properties of AEW&C were available from the WDA. For the observations described above we judged that due to the demands associated with protecting valuable assets in a hostile airspace, the six-person, multi-skilled team may find it more difficult than the six-person, dedicated team to fulfil the AEW&C Purpose-related Function of portraying the tactical situation and to fulfil the AEW&C Priority and Value of maintaining a knowledge edge. On the basis of these types of judgments, of the impact of the distribution of work functions on the AEW&C work domain, we generated requirements for a new AEW&C team design. For example, one of the requirements that we identified was that the primary responsibility of at least one team member in a small, multi-skilled team should be general maintenance of the tactical picture.

To design the AEW&C team, we studied all of the requirements from the table-top analyses and we created a team design that fulfilled those requirements. Amongst other things, this team design specified that the team should not be split into subteams and that team members should be multi-skilled. In addition, the team design specified 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.

When we presented this team design to the AEW&C System Program Office, military experts (including those with backgrounds in AWACS and E2C operations, which are similar to AEW&C) judged that this team design was better than the designs they had independently considered for AEW&C in the past. Consequently, the team design that we developed has been adopted for AEW&C operations. In addition, our analyses lead to modifications of the AEW&C technical-system specification so that it better supports the AEW&C team design. These alterations were made prior to the contract being signed with the selected manufacturer for AEW&C and therefore at no cost to the Australian Government.

6. Training strategies for managing human error

The final application of CWA involves the development of a new approach for training technical skills in error management (Naikar and Saunders, 2003). Some of the motivations for this research included, firstly, our observation that there is widespread recognition in the aviation community that human error is inevitable and, secondly, that despite this the training of technical skills in many aviation-related organisations remains focused almost solely on preventing errors rather than also on how to manage errors once they have occurred.

The training approach that we have developed for managing human error may be illustrated by characterizing work systems as having boundaries of safe operation (Rasmussen et al., 1994; Flach and Rasmussen, 2000). Accidents or incidents can occur when workers cross these boundaries by making errors. However, crossing the boundaries is inevitable; so errors will occur on occasion. Therefore, rather than simply training workers not to make errors in the first place, they should also receive training in error detection and error recovery. This means that workers should be given the opportunity to cross the boundaries of safe operation, at least in a training simulator, and to practice detecting the cues that the system is in an unsafe state and recovering the system to a safe state. Then, if workers cross the boundaries of safe operation during real operations, they are more likely to detect and recover from the error and consequently avert an accident or incident.

This training approach is different from Crew Resource Management or CRM (e.g., Helmreich et al., 1999), a technique that is becoming widely used in the aviation community. CRM focuses on non-technical skills for error management, for example, maintaining vigilance, and leadership and communication skills for managing an evolving situation. In contrast, the training approach that we have developed focuses on technical skills for operating or handling a system when it has crossed the boundaries of safe operation, or when it has been placed in an unsafe state, as a result of human error.

This training approach can lead to novel ways of training. Consider, for example, the training of procedures in both commercial and military aviation. The most common practice is to drill aircrew in executing the steps of a procedure until, it is hoped, they will get it right every time. But a slip or lapse in executing some part of a procedure is inevitable, as an examination of any accident or incident database will show. The training approach that we have developed suggests that rather than simply drilling aircrew in executing procedures to prevent errors from

Table 4
A sample of prompts relating to the different parts of the decision ladder for examining workers' error, error detection, and error recovery processes

Parts of the decision ladder	What was the error? Why didn't the workers detect the error? Why didn't the workers recover from the error?	How did the workers detect the error?	How did the workers recover from the error?
Observation	Did the workers fail to observe critical information?	What information or cues did the workers observe?	
Diagnosis	Did the workers find it difficult to diagnose the situation?	What was the workers' diagnosis of the situation?	
Option evaluation	Did the workers find it difficult to evaluate options?		What options did the workers consider? Why did the workers select/reject options?
Prioritisation of goals	Did the workers give precedence to alternative goals?		What were the workers' goals?
Planning of tasks and resources	Did the workers find it difficult to plan the tasks and resources required for dealing with the situation?		What tasks and resources did the workers plan to use to recover from the error?
Planning or selection of procedures	Did the workers find it difficult to plan or select procedures for dealing with the situation?		What procedure did the workers formulate to recover from the error? What standard procedure did the workers select to recover from the error?
Execution	Did the workers fail to execute the procedure as intended?		What procedure did the workers execute?

occurring, aircrew should also be given training in technical skills for dealing with the evolving situation if they make an error in executing a procedure. Therefore, at least in a training simulator, aircrew should be given the opportunity to not follow a procedure or parts of a procedure and to practise detecting and recovering from the 'error'.

In addition to a theoretical basis for training workers to manage human error, we have also developed a CWA-based technique for identifying specific training requirements for managing human error (Naikar and Saunders, 2003). This technique, which consists of three main steps, involves analysing accidents and incidents to examine the boundaries of safe operation that workers have crossed in the past and the problem-solving difficulties that workers have experienced in crossing these boundaries. Subsequently, this analysis can be used to develop training requirements in terms of the boundaries that workers should be given the opportunity to cross, or the unsafe states that workers should experience, during training and the problem-solving processes that they should practice to enable error detection and error recovery.

To illustrate, imagine a situation in which the pilot of an aircraft tries to execute a manoeuvre manually without first disengaging the autopilot. The pilot experiences difficulty in executing the manoeuvre because the autopilot is fighting him/her for control of the aircraft. However, the pilot perseveres with trying to complete the manoeuvre. The autopilot has a bank limit so when the aircraft reaches a 45° bank angle, as a result of the pilot's actions, the autopilot produces a fail tone and then disengages from controlling the aircraft. As the autopilot disengages while the pilot is exerting high stick forces in order to gain control of the aircraft, the aircraft is thrown into a hazardous attitude and then hits the ground.

The first step of the CWA-based technique is to identify the critical points in an accident or incident. In the situation described above, the first critical event occurred when the pilot tried to execute a manoeuvre manually without disengaging the autopilot. The second critical event occurred when the autopilot disengaged and produced a fail tone but the pilot did not respond to the tone.

The second step of the CWA-based technique involves using the decision ladder template from the CWA framework to examine workers' problem solving during each critical event. Table 4 shows a sample of prompts relating to the different parts of the decision ladder. By using these prompts to review accident or incident data, analysts can explore: the errors made by workers that placed the system in an unsafe state (second column of table); why the workers did not detect or recover from the error (second column of table); or how the workers detected (third column of table) and recovered (fourth column of table) from the error.

Fig. 8 illustrates this step for the first critical point in the example presented earlier, that is, when the pilot tried to execute a manoeuvre manually without first disengaging the autopilot. The numbers indicate the order in which the decision ladder should be followed. From this representation, we begin to understand that the pilot did not execute a procedure correctly (that is, the pilot tried to perform a manoeuvre manually without first disengaging the autopilot) and then had difficulty in detecting the error that

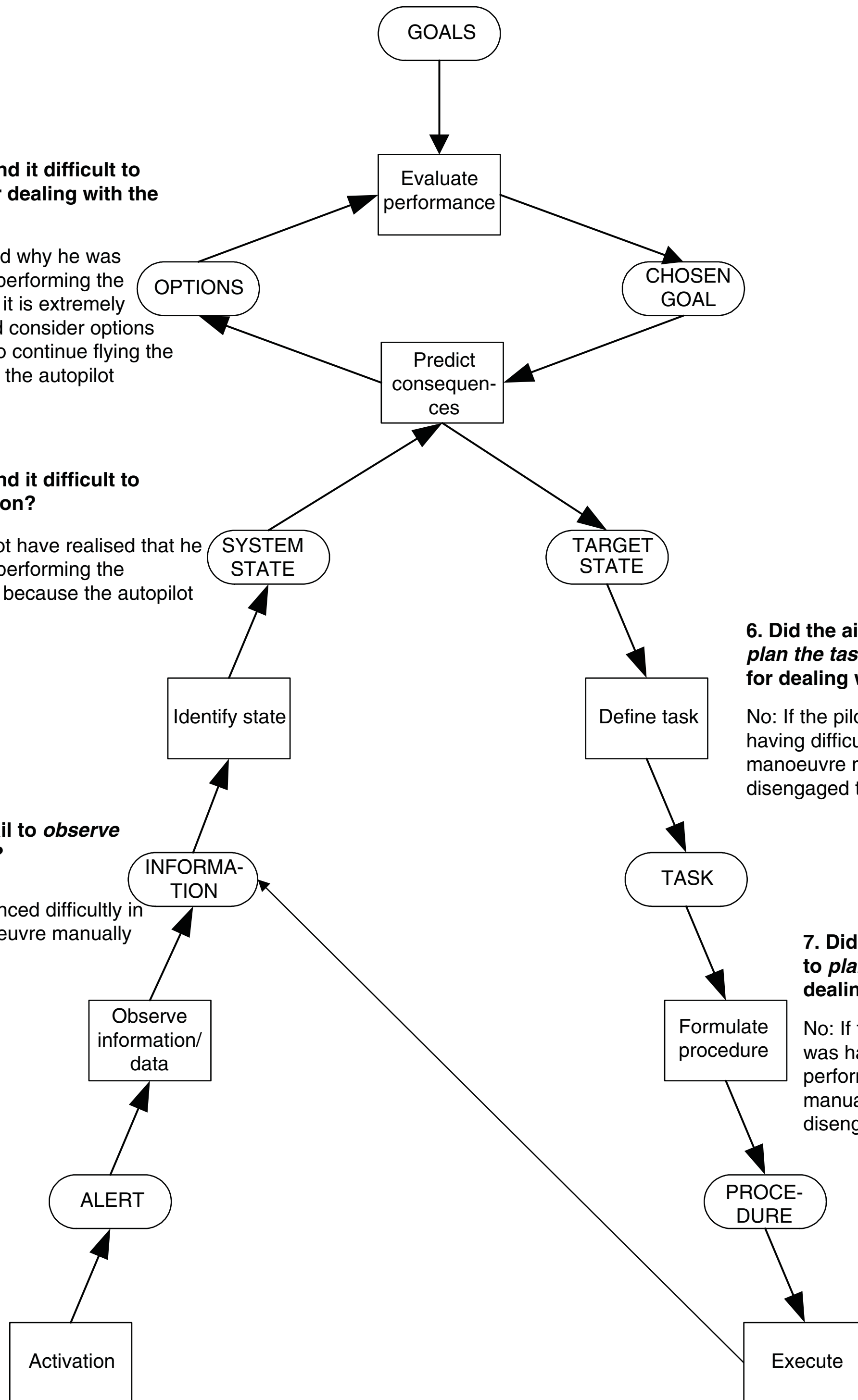

Fig. 8. A decision ladder for the first critical point in the hypothetical accident.

he/she had made. The difficulty that the pilot had in detecting the error was not because the pilot did not *observe* critical information (the pilot was aware that it was difficult to perform the manoeuvre) but rather because the pilot was unable to *diagnose* why he/she was finding it hard to execute the manoeuvre manually. If the pilot had made the right diagnosis, the pilot would probably have detected the error (that is, realised that he/she had forgotten to disengage the autopilot) and subsequently recovered from the error (that is, disengaged the autopilot while reducing stick forces).

Finally, the third step of the CWA-based technique involves specifying training requirements for managing human error on the basis of the preceding analysis. The training requirement that relates to the example presented above is to give aircrew the opportunity to perform a manoeuvre manually with the autopilot engaged so that they can experience the difficulty they would have in performing this manoeuvre. In addition, aircrew should practise disengaging the autopilot while exerting appropriate stick forces so that the aircraft is not thrown into a hazardous state when the autopilot relinquishes control of the aircraft. Then, if aircrew forget to disengage the autopilot before performing a manoeuvre manually on a real mission, they are more likely to recognise the cues that the autopilot is still engaged and disengage the autopilot to regain control of the aircraft without throwing the aircraft into a hazardous state.

To evaluate this new training approach for managing human error, we have applied the CWA-based technique for analysing accidents and incidents to the F-111, a strike aircraft in the Royal Australian Air Force. Specifically, we used the CWA-based technique to analyse three F-111 accidents and 21 F-111 incidents. The analysis of the F-111 accidents resulted in six training requirements and the analysis of the F-111 incidents resulted in eight training requirements (several of the incidents involved the same type of error).

To evaluate these training requirements, we interviewed several F-111 aircrew (pilots and navigators) and training instructors about the training requirements. For each training requirement, we asked the interviewees: (1) whether they already conducted the training that we had identified; (2) whether they thought that the training we had identified would be useful for helping them to deal with errors on real missions; and (3) whether they had been in an unsafe situation similar to the accident or incident that had motivated the training requirement.

Table 5 shows the number of "yes" responses against the total number of responses for each training requirement. For each training requirement, the majority of interviewees responded that they did not conduct the training we had identified. Those interviewees that indicated that they had conducted the training we had identified generally reported that they had been exposed to the training once before when the opportunity arose naturally through aircrew error. None of the training requirements were conducted systematically or documented in the F-111 training syllabus. The table also shows that the majority of interviewees indicated that the training would be useful for helping them deal with errors on real missions. A few of the interviewees responded that some of the training requirements were not useful because they were unlikely to make the type of error that had resulted in the training requirement. However, for every training requirement, several interviewees reported that they had been in an unsafe situation similar to the associated accident or incident, suggesting that the errors may not be impossible.

Table 5
The number of interviewees that responded "yes" to the interview questions against the total number of responses for each training requirement

Training requirements	Already done in training? Number responding "Yes" (total responses)	Useful? Number responding "Yes" (total responses)	Similar situation? Number responding "Yes" (total responses)
1	0 (10)	10 (10)	8 (10)
2	1 (14)	13 (14)	7 (14)
3	0 (13)	14 (14)	8 (13)
4	1 (13)	12 (13)	4 (13)
5	4 (14)	14 (14)	13 (13)
6	5 (12)	11 (11)	9 (12)
7	1 (12)	12 (12)	6 (12)
8	1 (12)	11 (12)	8 (12)
9	0 (12)	12 (12)	11 (12)
10	0 (12)	12 (12)	5 (12)
11	2 (12)	11 (12)	10 (12)
12	1 (12)	12 (12)	4 (12)
13	0 (12)	12 (12)	9 (12)
14	0 (12)	12 (12)	5 (12)

Given the results of the F-111 study, the Officer in Command of the F-111 group is interested in trialling this training approach for managing human error. If the results of the trial are positive, the next step is to determine whether the CWA-based technique for analysing accidents and incidents can be extended to systems that are operated by more than two workers. If these results are also positive, the Directorate of Flying Safety of the Australian Department of Defence is interested in implementing the technical training approach for error management throughout Defence aviation.

Finally, while this research has focussed on the analysis of previous accidents and incidents to identify training strategies for managing human error, CWA could also potentially provide a framework for a more proactive approach to error management. The training approach that we have advocated involves giving workers the opportunity to cross the boundaries of safe operation in a training simulator and to practice detecting the cues that the system is in an unsafe state and recovering the system to a safe state. Given that CWA provides a framework for identifying the different kinds of boundaries or constraints

on safe and effective operation, this technique could be used as a basis for systematically exploring: the kinds of boundaries that workers could potentially cross in a work system; the cues that would allow them to detect that the system is in an unsafe state if they cross those boundaries; and the behaviours that would allow them to recover the system to a safe state. The use of CWA to develop a proactive approach to error management is a key area for future research.

7. Conclusion

This paper has demonstrated the application of CWA to a variety of problems other than interface design. The paper has shown that CWA can be used to: identify training needs and training-system requirements; evaluate alternative system design proposals; develop team designs; and identify training strategies for managing human error. In addition, the paper has established that, for all of these applications, the CWA approach is both feasible and useful on industry projects: the training needs and training-system requirements that were identified by CWA were released in the request for tender documentation for the acquisition of a training system for F/A-18 aircraft; the CWA framework for evaluation was used to select the winning design proposal for the new AEW&C system; the CWA-based technique for team design led to a team design that has been adopted for AEW&C operations; and the CWA-based approach for accident and incident analysis was used to identify strategies for training F-111 pilots and navigators to detect and recover from human error.

While it is difficult to estimate the exact cost of using CWA on these projects, we believe that the cost associated with CWA was insignificant relative to the cost of the systems engineering processes or standard techniques that were used on these projects or relative to the total cost of the project. For example, we believe that the cost of using CWA to evaluate alternative design proposals for AEW&C was, at the most, five hundred thousand Australian dollars whereas the total cost of the AEW&C acquisition is estimated to be three billion Australian dollars. Moreover, CWA provided a useful complement to the systems engineering processes or standard techniques that were used on these projects because it addressed areas that were not well attended to by the latter. For example, systems engineering processes or standard techniques do not appear to have a theoretically based or systematic approach for designing teams for future, first-of-a-kind systems.

We acknowledge, though, that while we have shown that CWA is both feasible and useful on industry projects, we have not yet proven that CWA leads to better or more effective systems than standard approaches for system acquisition or system design and development. However, it is difficult to test this empirically without requiring excessive resources. For instance, to determine whether the WDA approach resulted in the selection of the best design proposal for AEW&C, it would be necessary to develop three systems based on the designs of Companies A, B, and C and to test the three systems in a set of representative scenarios.

In the longer term, when new systems like AEW&C and the training system for F/A-18 are brought into service, the performance of these systems will provide an indication of the effectiveness of the approaches that were used to produce these systems. However, it will be difficult, if not impossible, to isolate the contribution of CWA from other approaches. For example, an effective F/A-18 training system cannot be solely associated with CWA because standard techniques for training needs analysis were also used on this project. In addition, an effective AEW&C system cannot be attributed solely to the CWA-based technique for team design because other elements of the system design, such as the interface design and the design of physical subsystems, will also contribute to the performance of the AEW&C system. These issues with evaluating the effectiveness of CWA are not specific to this approach, however, but are also relevant to other techniques that are used for system design and development.

Given the various complications that are associated with establishing the effectiveness of techniques that are used on industry projects, these techniques are rarely evaluated in a formal way (Czaja, 1997). Instead, the criteria that are typically used include the ability to influence practice and usefulness (Whitefield et al., 1991; Vicente, 1999). The CWA approach fulfilled both of these criteria on the four projects that were discussed in this paper. The adoption of CWA techniques by other researchers and practitioners will provide further tests of the CWA approach against these criteria.

The applications of CWA that have been presented in this paper were developed in the context of complex, military systems. Another limitation of our research, therefore, is that we do not know the extent to which these applications of CWA generalise to other domains. By documenting these applications of CWA to the military domain, however, this paper will allow other researchers and practitioners to explore the relevance of these applications to additional domains.

Finally, to apply CWA to the types of applications that have been discussed in this paper—or to apply CWA to interface design—analysts will need considerably more information about how to perform CWA than what has been provided in this paper. Some guidelines for performing WDA are provided by Burns and Hajdukiewicz (2004) and Naikar et al. (in press). In addition, Naikar et al. (in press) provide guidelines for performing ConTA. A methodology for performing WDA and ConTA, however, can never be completely specified. It is therefore important to have a sound understanding of the theoretical foundations of CWA so that the way in which WDA and ConTA is performed is not inconsistent with theory. The most comprehensive resources for the theory of CWA are the texts by Rasmussen et al. (1994) and Vicente (1999).

Acknowledgments

I thank Anna Moylan and Robyn Hopcroft from the Defence Science and Technology Organisation for their assistance with preparing this manuscript.

References

Bisantz, A.M., Roth, E.M., Brickman, B., Gosbee, L., Hettinger, L., McKinney, J., 2003. Integrating cognitive analyses in a large scale system design process. International Journal of Human Computer Studies 58, 177–206.

Burns, C.M., 2000. Putting it all together. Improving display integration in ecological displays. Human Factors 42, 226–241.

Burns, C.M., Hajdukiewicz, J.R., 2004. Ecological Interface Design. CRC Press, Boca Raton, FL.

Burns, C.M., Bryant, D.J., Chalmers, B.A., 2000. A work domain model to support shipboard command and control. 2000 IEEE International Conference on Systems, Man, and Cybernetics . Piscataway, NJ: Institute of Electrical and Electronics Engineers, pp. 2228–2233.

Burns, C.M., Bisantz, A.M., Roth, E.M., 2004. Lessons from a comparison of work domain models: Representational choices and their implications. Human Factors 46 (4), 711–727.

Card, S.K., Moran, T.P., Newell, A., 1983. The Psychology of Human-Computer Interaction. Lawrence Erlbaum Associates, Hillsdale, NJ.

Czaja, S.J., 1997. Systems design and evaluation. In: Salvendy, G. (Ed.), Handbook of Human Factors and Ergonomics, second ed. Wiley, New York, pp. 17–40.

Davis, L.E., Wacker, G.L., 1982. Job design. In: Salvendy, G. (Ed.), Handbook of Industrial Engineering. Wiley, New York p. 2.5.1–2.5.31.

Department of the Air Force, 1993. Instructional system development. AF Manual no. 36-2234. Author, Washington, DC.

Dinadis, N., Vicente, K.J., 1999. Designing functional visualization for aircraft systems status displays. International Journal of Aviation Psychology 9, 241–269.

Dubrovsky, V., Piscoppel, A., 1991. Toward a framework for structured job-collaboration design. In: Proceedings of the Human Factors Society 35th Annual Meeting, Santa Monica, CA: Human Factors and Ergonomics Society, pp. 959–963.

Flach, J.M., Rasmussen, J., 2000. Cognitive engineering: designing for situation awareness. In: Sarter, N.B., Amalberti, R. (Eds.), Cognitive Engineering in the Aviation Domain. Lawrence Erlbaum Associates, Mahwah, NJ, pp. 153–179.

Gualtieri, J., Elm, W.C., Potter, S.S., Roth, E.M., 2001. Analysis with purpose: Narrowing the gap with a pragmatic approach.In: Proceedings of the Human Factors and Ergonomics Society 45th Annual Meeting. HFES, Santa Monica, CA, pp. 444–448.

Hackman, J.R., Oldham, G.R., 1980. Work redesign. Addison-Wesley, Reading, MA.

Helmreich, R.L., Klinect, J.R., Wilhelm, J.A., 1999. Models of threat, error, and CRM in flight operations. In: Proceedings of the Tenth International Symposium on Aviation Psychology, Ohio State University, Columbus, OH, 3–6 May 1999, pp. 677–682.

Kirwan, B., Ainsworth, L.K. (Eds.), 1992. A Guide to Task Analysis. Taylor & Francis, London.

Leveson, N.G., 2000. Intent specifications: An approach to building human-centred specifications. IEEE Transactions on Software Engineering 26, 15–35.

Linegang, M.P., Lintern, G., 2003. Multifunction displays for optimum manning: Towards functional integration and cross-functional awareness. In: Proceedings of the Human Factors and Ergonomics Society 47th Annual Meeting. HFES, Santa Monica, CA, pp. 1923–1927.

Lintern, G., Naikar, N., 1998. Cognitive work analysis for training system design. In: Proceedings of the Australasian Computer Human Interaction Conference (OzCHI'98). IEEE Computer Society Press, Los Alamitos, CA, pp. 252–259.

Lintern, G., Naikar, N., 2000. The use of work domain analysis for the design of training systems. In: Proceedings of the HFES/IEA 2000: HFES, Santa Monica, CA, pp. 198–201.

Miller, R.B., 1953. Formal analytical structure for manned systems analysis. Ohio State University Press, Columbus.

Naikar, N., Sanderson, P.M., 1999. Work domain analysis for training-system definition and acquisition. International Journal of Aviation Psychology 9, 271–290.

Naikar, N., Sanderson, P.M., 2001. Evaluating design proposals for complex systems with work domain analysis. Human Factors 43, 529–542.

Naikar, N., Saunders, A., 2003. Crossing the boundaries of safe operation: An approach for training technical skills in error management. Cognition Technology and Work 5, 171–180.

Naikar, N., Pearce, B., Drumm, D., Sanderson, P.M., 2003. Designing teams for first-of-a-kind, complex systems using the initial phases of cognitive work analysis: Case study. Human Factors 45, 202–217.

Naikar, N., Moylan, A., Pearce, B., in press. Analysing activity in complex systems with cognitive work analysis: Concepts, guidelines, and case study for control task analysis. Theoretical Issues in Ergonomics Science.

Rasmussen, J., 1998. Ecological interface design for complex systems: An example: SEAD—UAV systems. AFRL-HE-WP-TR-1999-0011. AFRL, Human Effectiveness Directorate, Dayton, OH.

Rasmussen, J., Pejtersen, A.M., Goodstein, L.P., 1994. Cognitive Systems Engineering. Wiley-Interscience, New York.

Reising, D.V.C., Sanderson, P.M., 1998. Designing displays under ecological interface design: Towards operationalizing semantic mapping. In: Proceedings of the Human Factors and Ergonomics Society 42nd Annual Meeting. HFES, Santa Monica, CA, pp. 372–376.

Schraagen, J.M., Chipman, S.E., Shalin, V.L. (Eds.), 2000. Cognitive Task Analysis. Lawrence Erlbaum Associates, Mahwah, NJ.

Seamster, T.L., Redding, R.E., Kaempf, G., 1997. Applied Cognitive Task Analysis in Aviation. Ashgate, London.

Taylor, F.W., 1911. The Principles of Scientific Management. Harper and Row, New York.

Vicente, K.J., 1992a. Multilevel interfaces for power plant control rooms I: An integrative review. Nuclear Safety 33 (3), 381–397.

Vicente, K.J., 1992b. Multilevel interfaces for power plant control rooms II: A preliminary design space. Nuclear Safety 33 (4), 543–548.

Vicente, K.J., 1999. Cognitive Work Analysis: Toward Safe, Productive, and Healthy Computer-based Work. Lawrence Erlbaum Associates, Mahwah, NJ.

Whitefield, A., Wilson, F., Dowell, J., 1991. A framework for human factors evaluation. Behaviour and Information Technology 10, 65–79.

Zsambok, C.E., Klein, G., 1997. Naturalistic Decision Making. Lawrence Erlbaum Associates, Mahwah, NJ.