6 Cognitive Work Analysis for Air Defense Applications in Australia

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ABSTRACT

Cognitive Work Analysis (CWA; Rasmussen, Pejtersen & Goodstein, 1994; Vicente, 1999) is most familiar to cognitive engineers from its successes in the area of interface design. In this report, we describe how we have used CWA in a variety of other contexts at the Defence Science and Technology Organisation (DSTO) in Australia. First, we describe the five analytic techniques of CWA, and we show how CWA can be used throughout a system's life cycle, from requirements definition to system retirement. Second, we provide specific examples of projects from the air defense domain in which we have used CWA. These projects include (1) evaluating alternative designs for Airborne Early Warning and Control (AEW&C) aircraft, (2) evaluating human-system integration solutions for AEW&C, (3) identifying training needs for F/A–18 pilots and developing functional requirements for a training system that meets those needs, and (4) designing information work spaces for command and control. These examples give strength to the argument that CWA can be used just as effectively in areas other than interface design where the professional contribution of cognitive engineers is required.

6.1 BACKGROUND TO CWA

6.1.1 Introduction

Cognitive Work Analysis (CWA) is a systems-based approach for analyzing, modeling, designing, and evaluating complex sociotechnical systems (Rasmussen, Goodstein, & Pejtersen, 1994; Vicente, 1999). CWA is therefore one of the many different techniques for analyzing work that cognitive systems engineering can call upon. The specific focus of CWA, though, is to support operator adaptation and flexibility in complex, real-time work domains, especially during unanticipated contingencies. CWA therefore appears particularly well suited to air defense domains, where an opponent will often wish to create unanticipated situations to achieve a tactical advantage.

CWA aims to support operator adaptation to unexpected circumstances by designing interfaces that are based, not on *typical* or *optimal* work patterns, but on the *constraints* that shape the work patterns in the first place. During novel situations, workers usually cannot rely on work procedures that were planned in the context of typical or expected situations. Rather, to prevent system failure, workers must adapt their behavior to the particular situation at hand, without crossing the boundaries on safe and effective operation in that work domain. Thus, in designing computer-based interfaces, designers should make visible the constraints or boundary conditions on safe and effective operation in that work domain. Workers are then more likely to respond appropriately when something unusual happens.

The concept of constraints is therefore critical to CWA. Constraints are factors that shape workers' activity by imposing limits as well as offering possibilities for safe and effective action. In Figure 6.1, activity is seen as a region of possible action trajectories in the center of the diagram while some of the key factors that place constraints on safe and effective action are shown around the edges. In most work systems, there are a large number of possible action trajectories that do not violate the constraint-based boundaries of that work space. Thus, an analysis of the specific sequences of behavior that should happen or typically happen in a work space is bound to be incomplete. Rather, activity is more robustly described by the constraints that shape the action trajectories.

CWA consists of five modeling techniques that are tailored for analyzing constraints. Figure 6.2 summarizes the five analytic techniques of CWA, the information each technique provides, and the form of the analytic product in which the information is delivered. In the following sections, we provide more detailed descriptions of the five analytic techniques of CWA.

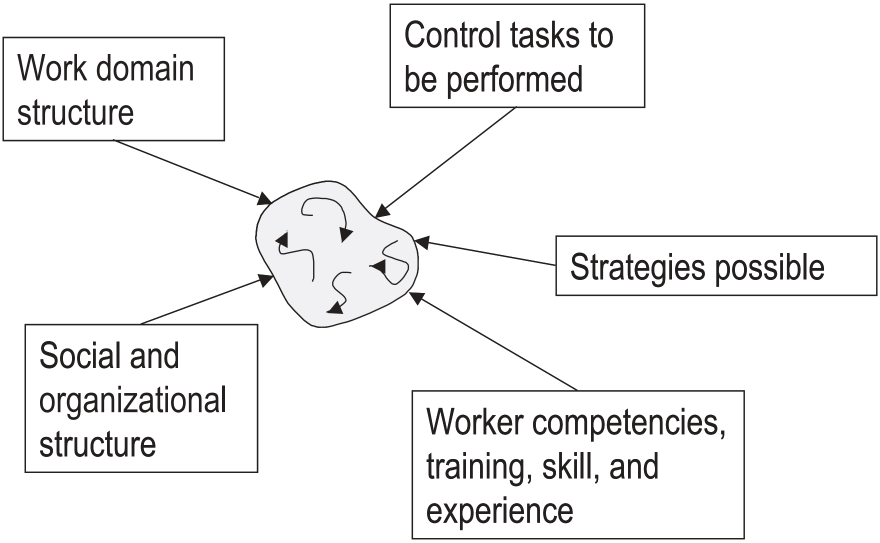


Figure 6.1: Five general areas of constraints (boxes) work together to shape possible and effective action trajectories (arrows in center area).

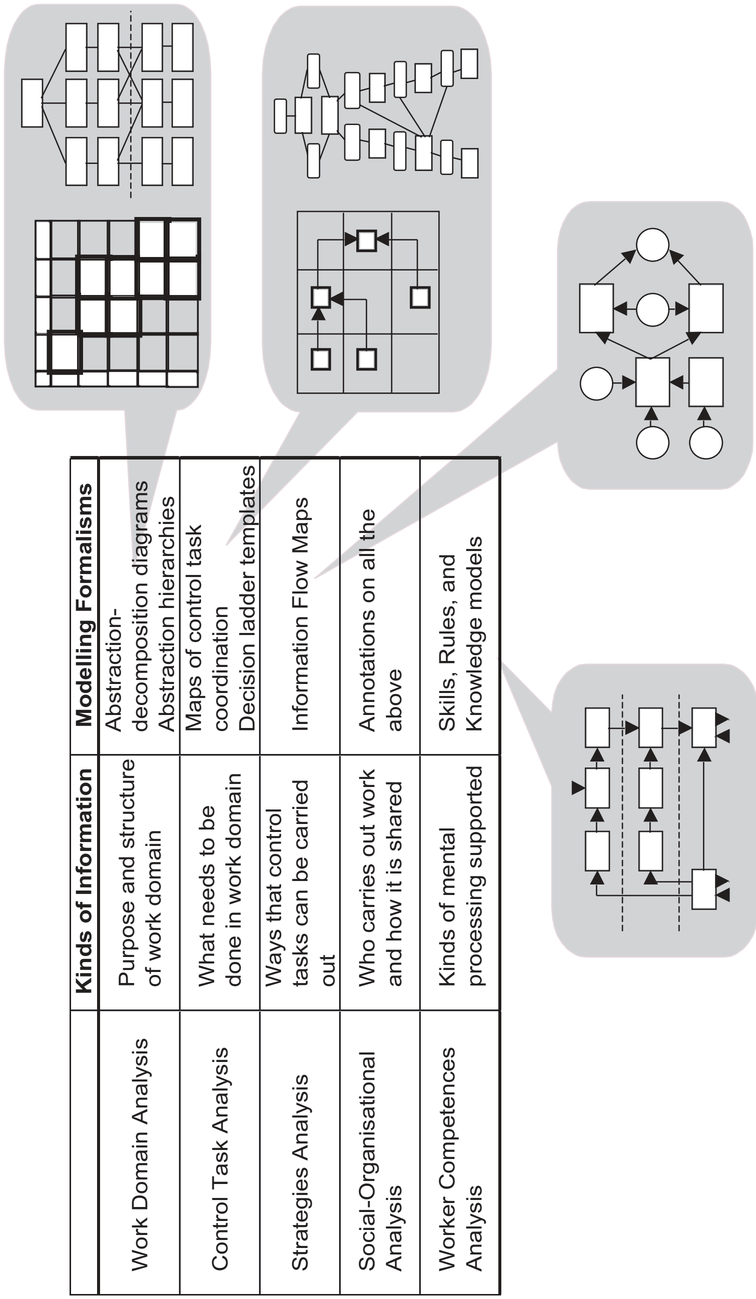
6.1.2 Work Domain Analysis

Work domain analysis models the purposive and physical constraints of the system in which activity take places. These constraints include the (1) functional purposes or high-level objectives of the system, (2) priorities and values that are preserved during system operation, (3) purpose-related functions that are executed and coordinated to achieve system goals, (4) physical functions, such as the functionality afforded by the physical devices of the system, and (5) physical form, such as the physical devices themselves. These constraints are typically described in an abstraction hierarchy or within an abstraction-decomposition space.

The constraints identified by work domain analysis are event-independent. This means that the functional purposes, priorities and values, and purpose-related functions of a system, as well as its physical resources (physical function and physical form), are relevant across a broad range of scenarios or situations, including unanticipated events.

6.1.3 Control Task Analysis

Control task analysis focuses on what needs to be done in a work domain for a system to achieve its functions and objectives. In particular, this analysis identifies activities having to do with information gathering and situation analysis,



	Kinds of Information	Modelling Formalisms
Work Domain Analysis	Purpose and structure of work domain	Abstraction-decomposition diagrams Abstraction hierarchies
Control Task Analysis	What needs to be done in work domain	Maps of control task coordination Decision ladder templates
Strategies Analysis	Ways that control tasks can be carried out	Information Flow Maps
Social-Organisational Analysis	Who carries out work and how it is shared	Annotations on all the above
Worker Competences Analysis	Kinds of mental processing supported	Skills, Rules, and Knowledge models

Figure 6.2: Five phases of CWA with iconic representations of their most familiar analytic products.

hypothesis generation and testing, planning, and execution. The decision ladder template is most often used for modeling control tasks. Later in this paper, we also discuss our extension of control task analysis, which we have called *Temporal Coordination Control Task Analysis*, because it shows the constraints on the coordination of activities over time.

6.1.4 Strategies Analysis

Strategies analysis focuses on ways of performing control tasks. Typically, there are several strategies for performing a single control task. For example, an electrician could use either a pattern-recognition strategy or a decision-table strategy to diagnose problems with faulty equipment. The two strategies require very different kinds of cognitive resources; the former strategy relies on the expertise of the electrician whereas the latter strategy relies on the expertise of the person who developed the decision table. The modeling template most often used for strategies analysis is an information flow map.

6.1.5 Socio-Organizational Analysis

Socio-organizational analysis is concerned with how work is allocated among human workers and intelligent agents. The allocation of work might be across different parts of the work domain, control tasks, or strategies. For example, the strategy of using a decision table in electronic troubleshooting might be distributed across human workers and automation; a human worker enters the symptoms of faulty equipment into a computer that responds with a list of potential faults and options for repair. The abstraction hierarchy or abstraction-decomposition space, decision ladders, and information flow maps can all be used as templates for work allocation.

6.1.6 Worker Competencies Analysis

Worker competencies analysis focuses on the competencies (e.g., knowledge, skills) that workers need for carrying out the work of the system. Hence, it is only at this phase of the CWA framework that the particular constraints of human workers are considered, because the constraints identified in the initial phases of CWA will affect the analysis of competencies. For example, if a control task is allocated purely to machine automation, then human workers will not require skills for performing this control task. Rasmussen's (1986) skills, rules, and knowledge taxonomy can be used for matching work demands to human capabilities and limitations.

6.2 CWA AND THE SYSTEM LIFE-CYCLE

Many researchers and human factors practitioners have commented that carrying out a full CWA is a daunting task. However, we argue, first, that there are many investigations where this level of effort is warranted and, second, that the products of CWA can be put to multiple uses throughout the system life-cycle. Hence, CWA ultimately provides benefits that are far greater than the initial investment in time and resources (Sanderson, Naikar, Lintern, & Goss, 1999). Another paper that echoes the same point is Leveson (2000) in which she discusses the application of CWA-based ideas to the construction of a design rationale for software systems.

Figure 6.3 illustrates some of the stages in the system life-cycle where one or more CWA analytic products may be useful. The figure shows the five phases of CWA in its columns and the different stages in the system life-cycle in its rows. Cells describe how the products of CWA modeling may contribute at each point in the system life-cycle. Some of the cells have been filled in with uses, but this does not mean that other uses might not be found at the same point. Other cells have been left empty, but this does not mean that they have nothing to contribute to the stage of the system life cycle indicated. We expect that with further use of CWA across different contexts, we will be able to flesh out this table with more examples.

In the remainder of this section we briefly review the stages of the system life-cycle, and we outline how CWA might inform each stage. Later in this paper, we provide specific examples of how we have used CWA at different points in the system life-cycle. We focus mostly on work domain analysis because that is where we have most experience, but this should not be taken to belittle the actual and potential contributions of other phases.

6.2.1 Requirements

At the outset of developing a system, work domain analysis is the primary framework for identifying requirements. It helps analysts think about why a new system should exist, what functions it should implement, and what physical devices are necessary. In addition, work domain analysis provides a framework for putting requirements into context, for example, by indicating whether the requirements relate to the purposes and priorities of the system, or whether the requirements relate to the physical devices of the system. For our work on evaluating designs for AEW&C, we developed a work domain analysis that was essentially constructed from requirements documents (Naikar & Sanderson, 2000a, b).

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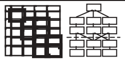
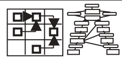
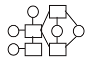
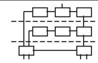
				*Annotation of other diagrams*	
	Purpose and structure	Control tasks and coordination	How control tasks carried out	Who does what and with whom	Mental processes entailed (SRK)
Requirements	develop				
Specifications	develop	develop			
Design					
Hardware, software	define				
Control tasks	given	define			
Dialog support		given	define		
Actor roles			given	define	
Interface formats				given	define
Simulation	means/ends	activities	options	agent(s)	ag. properties
Evaluation of design(s)	char/eval/comp	char/eval/comp	char/eval/comp	char/eval/comp	char/eval/comp
Implementation	guide				
Test	judge match	judge perf	judge process	judge roles	judge workload
Operator Selection				guide	guide
Operator Training	guide	guide	guide	guide	guide
Routine use	describe	describe	describe	describe	describe
Non-routine use	describe	describe	describe	describe	describe
Maintenance	describe				
Research (HF studies)	system ID	task contexts	tools, options	human context	support needs
Upgrades	model effects	model effects	model effects	model effects	model effects
System retirement	judge shortfall	judge shortfall			

Figure 6.3: Actual and potential uses of the five phases of CWA over the life-cycle of a complex sociotechnical system. The five phases of CWA have been abbreviated as follows: Work Domain Analysis (WDA), Control Task Analysis (CTA), Strategies Analysis (SA), Socio-Organizational Analysis (SOA), and Worker Competencies Analysis (WCA).

6.2.2 Specification

In the specifications stage, more detail is needed for design to proceed. A system developer needs to know what must be done in a work domain for the system to achieve its functions and purposes. Therefore, the knowledge that a control task analysis provides is important for building specifications for the system. In addition, Leveson (2000) has found that an extension of work domain analysis, to capture the design intent in complex software engineering projects, is useful for developing "intent specifications."

6.2.3 Design

As outlined in Vicente (1999), design has been classified into five general stages that reflect what each of the five phases of CWA offers. Hardware and software needs (models, databases, sensors, etc) can be described principally by work domain analysis, even though it may be guided by information from other phases. Control tasks can be identified by control task analysis, provided we know the work domain constraints (thus "given" under work domain analysis).

Dialogue support can be informed by strategies analysis, given we know what the control tasks are. The definition of actor roles, including allocation of function and coordination structures, can be described with socio-organizational analysis, given we know what the effective strategies are. Finally, the format of interfaces and visual displays can be informed by worker competencies analysis, given we know what the work allocation is.

6.2.4 Simulation

Simulation takes several forms. First, simulation refers to modeling events and the system's response to events. This will not be discussed in detail here but an example of control task analysis providing the foundation for agent-based simulation can be found in Sanderson et al. (1999). Second, simulation refers to the development of full- or part-task simulators for supporting training, further system development, etc. Later in this chapter, we will show how work domain analysis can be used for defining the requirements of large-scale training simulators (see also Lintern & Naikar, 2000; Naikar & Sanderson, 1999).

6.2.5 Evaluation of Designs

CWA provides us with tools for evaluating different designs during the development of a system. Work domain analysis, in particular, has a unique "summarizing" role in this respect. With this framework, alternative designs may be evaluated in terms of how well the technical solution (physical form and physical function) supports the purpose-related functions, priorities and values, and functional purposes of the work domain (Naikar & Sanderson, 2000a, b). In addition, control task analysis can be used as a backdrop for evaluating the human-system integration solutions of alternative design proposals (Sanderson & Naikar, 2000). Both of these projects will be discussed in more detail later in this paper.

6.2.6 Implementation

CWA products have the potential to guide the implementation process. In particular, they provide reference documents to consult while a design is being realized. For example, Leveson's (2000) addition of a "refinement" dimension to the abstraction-decomposition space is a recognition of how CWA products might guide implementation while at the same time evolving with it.

6.2.7 Test

As implementation proceeds, CWA can guide the testing process, particularly if a part- or full-scale simulator is available. Work domain analysis has an important role to play here. Groupings of system functions and physical elements, at their present stage of development, can be tested in terms of (1) whether they achieve their collective ends (the abstraction dimension), and (2) whether they function effectively as wholes (the decomposition dimension). Thus, work domain analysis allows testing of whether the functional structure of the system that emerges from implementation matches the analysis that was initially drawn up. Similarly, to the extent that a simulator or field context makes possible, CWA also allows testing of whether the system under development supports the necessary control tasks, strategies, role allocation and coordination structures, and operators' cognitive capabilities.

6.2.8 Operator Selection

Operator selection can be informed by the competencies that workers require to carry out the work of the proposed system. Thus, worker competencies analysis is highly relevant to this stage of the system life-cycle. However, because worker competencies are affected by how work has been allocated across human and machine agents, socio-organizational analysis also has a role to play here.

6.2.9 Operator Training

CWA can inform training in powerful ways that focus more on satisfying the functional purposes of a work domain by adapting behavior rather than by evoking procedures (Lintern & Naikar, 1999; Naikar & Sanderson, 1999; Naikar, Sanderson, & Lintern, 1999). Thus, work domain analysis identifies training needs in terms relating to the essential functional structure of the work domain rather than to specific trajectories of behavior. Similarly, control task analysis identifies training needs as a set of "problems to solve" rather than as specific steps for solving problems. strategies analysis identifies training needs as multiple strategies that workers can use for performing control tasks rather than as an idealized or one best strategy. Socio-organizational analysis identifies training needs relating to a configurable work allocation structure rather than to a fixed structure. Finally, worker competencies analysis identifies training needs in terms of different levels of mental processes rather than a single, fixed level.

6.2.10 Routine, Nonroutine, and Maintenance Activity

CWA can be used to describe routine, nonroutine, and maintenance activity within a system. Indeed, much of Rasmussen's work while developing the modeling techniques used in CWA was descriptive in nature (Rasmussen et al., 1994). Descriptions of different kinds of activity can be thought of as animations and annotations on the products of CWA modeling, to show, for example, how a problem-solving sequence might be traced as a trajectory over the work domain, a chain of control tasks, a choice of a particular strategy, an interaction between different agents, or an exercise of certain cognitive competencies.

6.2.11 Research (HF Studies)

CWA can inform the design and operationalization of research programs in important ways (see Vicente, 1999). We have started to use CWA to ensure the representative design of experiments examining crew coordination and display design. For example, temporal coordination control task analysis gives us a profile of the control tasks within a phase of operation, and the temporal, logical, and structural coordination between those tasks. The temporal coordination control task analysis therefore sketches the "ecology" of the work environment that must be recreated or simulated in a laboratory study so that the empirical investigation is conducted in a representative setting.

6.2.12 Upgrades

CWA provides a framework for describing and predicting the impact of technological change. Using examples from elevator system design and the introduction of automated charting in an anesthesia environment, Benda and Sanderson (1999a, 1999b) have demonstrated that both work domain analysis and control task analysis can be extended to show how changes in physical devices and physical functioning create new constraints or affordances for activity that may have the ultimate effect of changing the nature of the work domain itself. For example, the automated patient record may afford the function of relating patient outcomes to preoperative events. Similar uses of CWA have been found for the F/A–18 upgrade and this will be discussed later in this chapter.

6.2.13 System Retirement

Finally, we envisage that CWA would be useful in making the decision to retire or decommission a system. A work domain analysis of the broader work context may show that a particular system is no longer helpful or competitive in meeting the functional purpose of the work domain. In addition, control task analysis may be useful for revealing shortfalls in the relevance or effectiveness with which control tasks are carried out.

6.2.14 Examples of CWA in Context

Having provided a brief survey of the possible uses of CWA at all stages of the system life-cycle, we now turn to four examples from our own work over the last two years. The four examples describe (1) the use of work domain analysis for evaluating alternative designs for an AEW&C system, (2) an extension of control task analysis for analyzing human-system integration solutions for AEW&C, (3) the use of work domain analysis for identifying training needs of F/A–18 pilots, and for defining functional requirements for a training system that meets those needs, and (4) an outline of how all the phases of CWA can be used for specifying the information needs for command and control. Although we are unable to describe these projects in detail here, we cite our other publications for more information about this work.

6.3 EVALUATION OF DESIGNS

One of our most successful applications of CWA at DSTO involved supporting the Australian Defence Force during the acquisition of a fleet of AEW&C aircraft. This system, which is valued at $3 billion, is being manufactured by Boeing in the United States. When it is delivered to Australia, the primary role of AEW&C will be to conduct surveillance and to coordinate the activity of defense assets in an allocated area of operations. Each aircraft will be equipped with a suite of physical devices including onboard sensors, satellite intelligence links, communications systems, and a work station for up to ten crew members. AEW&C is, therefore, one of the most complex systems to which CWA has been applied to date.

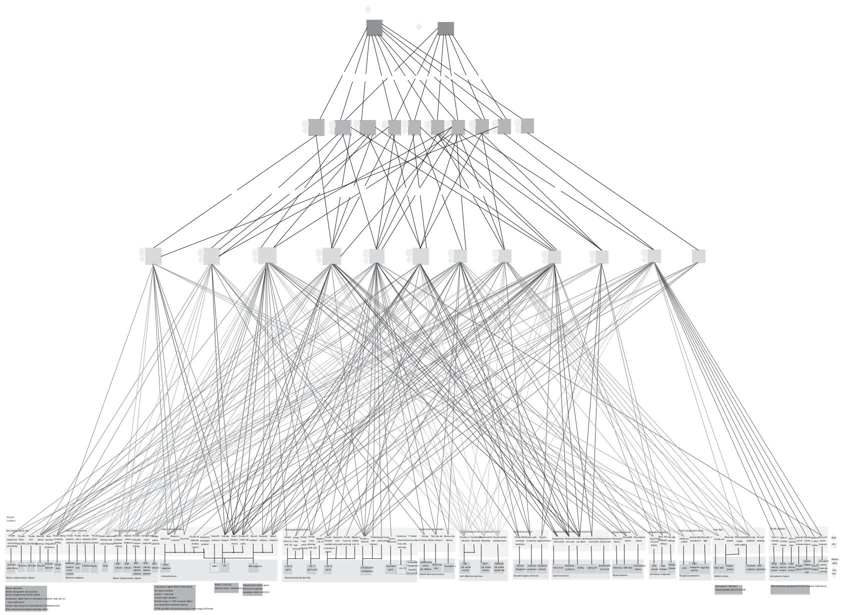
Our use of CWA occurred during the early stages of procurement when a formal evaluation of alternative design proposals for AEW&C was being conducted (Naikar & Sanderson, 2000a, b). Three potential AEW&C designs had been submitted by Boeing, Raytheon E-Systems, and Lockheed Martin and, initially, the AEW&C Project Office had planned to use only two techniques to select the winning design. The two techniques, technical and operational, are standard systems engineering techniques that are commonly used for procuring large-scale military systems (Department of Defence, 1995, 1999). For the technical evaluation, evaluators were to assess the technical strengths and limitations of each of the physical subsystems of AEW&C, for example, its radar, communications, and navigation systems. For the operational evaluation, evaluators were to use *Monte Carlo* simulation to test how computational models of each of the three designs would perform in six mission scenarios.

During a preliminary evaluation of the three designs, however, the AEW&C Project Office realized that the technical evaluation would produce a series of disparate reports about the physical devices of AEW&C. Thus, a radar report might indicate that design "A" was better than designs "B" and "C," whereas a communications report might indicate that design "B" was better than designs "A" and "C," and so on. The Project Office quickly became very concerned about how they would integrate the recommendations of several reports to reach a final decision about the best AEW&C design.

When this problem was presented to the evaluation team, of which we were members, it struck us that the reason for designing all these physical devices into a single system was to support a distinct set of functions, priorities and values, and purposes. Consequently, we could use work domain analysis to evaluate all physical-device solutions against these high-level functional properties. By comparing all the designs against the same set of functional criteria, it would be easier to select the best overall AEW&C design. After convincing the AEW&C Project Office that work domain analysis could be used to solve the "integration problem," we began to develop this approach to evaluation in the final year of tender evaluation (known as *source selection* in the U.S.).

Our first step was to develop an abstraction hierarchy for AEW&C. We were able to put together an initial representation from reviewing several AEW&C documents. For example, the AEW&C *concept of operations* provided information about the purposive functions of AEW&C (first three layers of the abstraction hierarchy) whereas the AEW&C *system specification* provided information about the physical functions and physical subsystems of AEW&C (last two layers). We then worked with several subject-matter experts, including military personnel and defense scientists, to revise and refine our initial characterization.

Figure 6.4 provides (1) a global view of the AEW&C abstraction hierarchy that we developed, and (2) a sample of functions from each layer of the AEW&C abstraction hierarchy. Using the abstraction hierarchy, the AEW&C evaluation team could trace the impact of physical-subsystem designs on the higher level functions of AEW&C. For example, evaluators could trace that a radar with a long range would allow AEW&C to gather information about entities at a greater distance from the platform, thus enhancing the timeliness with which entities are detected, tracked, and identified. On the other hand, a radar with a long range would also transmit electronic emissions over greater



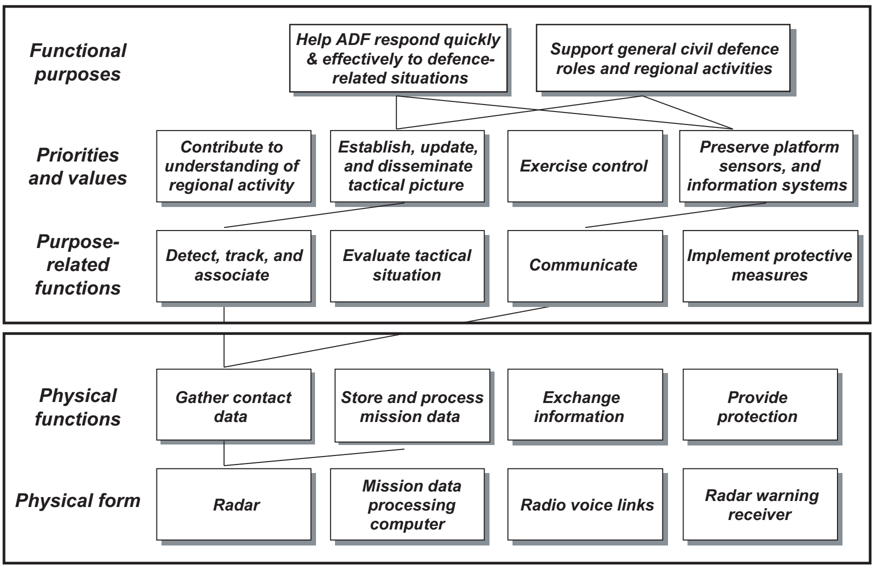


Figure 6.4: (a) A global view of the AEW&C abstraction hierarchy.
(b) A sample of functions from each layer of the AEW&C abstraction hierarchy.

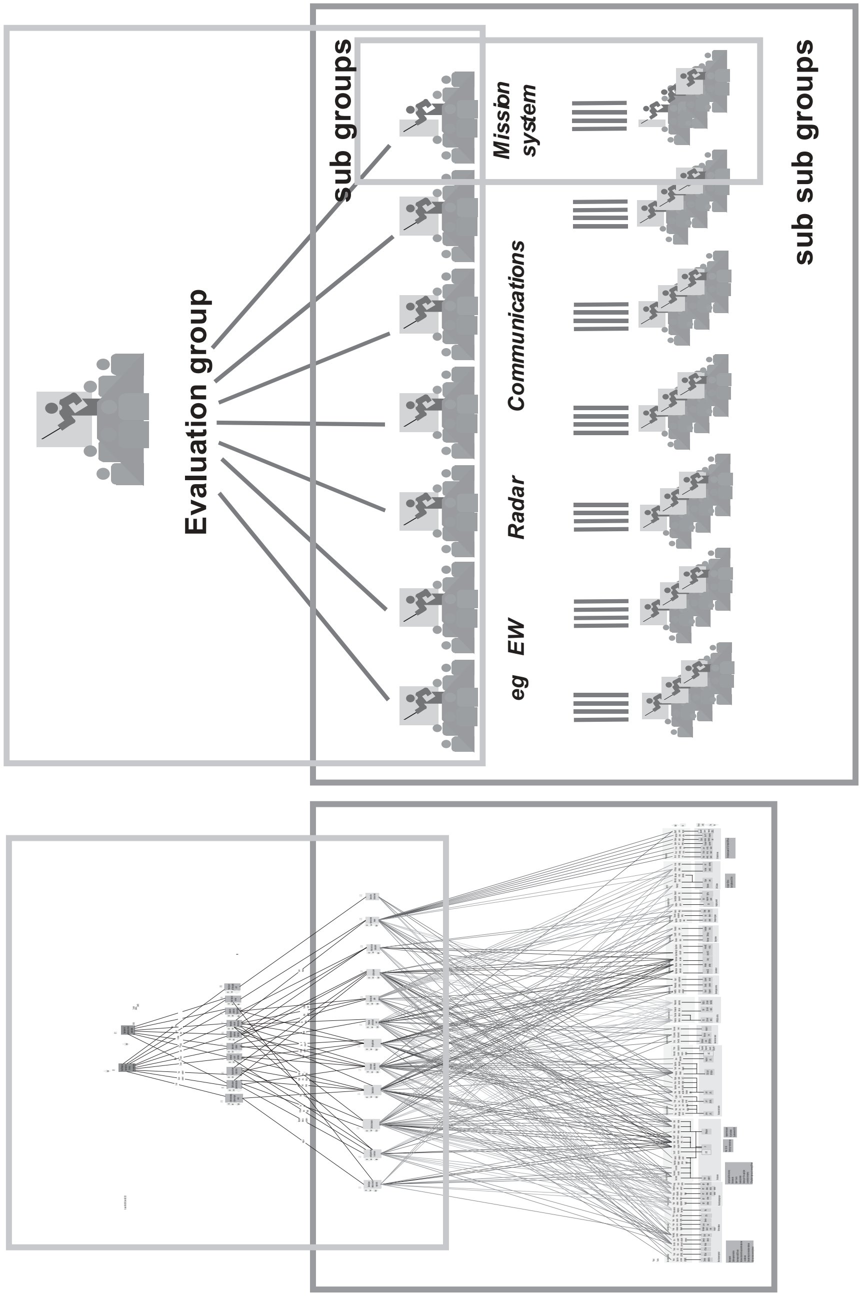


Figure 6.5: Structure of the group responsible for evaluating AEW&C designs.

distances, thereby communicating the presence of the AEW&C platform more broadly, which would compromise its survivability.

As well as constructing the AEW&C abstraction hierarchy, we also developed a process for using work domain analysis to evaluate AEW&C designs. This process took advantage of the structure of the evaluation team that had been set up for the technical evaluation (Figure 6.5). This team had been decomposed into subgroups that were responsible for carrying out a technical evaluation of a set of physical devices. For the work domain analysis-based evaluation, each subgroup evaluated how well the physical-device solutions supported the purpose-related functions of AEW&C. Following this, the leader of the evaluation team and his assistants from each of the subgroups evaluated the impact at the purpose-related functions layer against the priorities, and values, and functional purposes of AEW&C. We note that Sanderson has developed a Microsoft Excel™ spreadsheet for tracking and recording these types of judgments.

The evaluation team did not find this process overly taxing and in a briefing to the Deputy Secretary of the Department of Defence, the AEW&C Project Office singled out work domain analysis for its usefulness to the AEW&C acquisition. As well as solving the "integration problem," the AEW&C Project Office found it useful that they were able to express the results of the evaluation in terms of military utility, such as the purpose-related functions, priorities and values, and functional purposes of AEW&C (rather than in terms of technical properties). In addition, they thought that work domain analysis provided a good "sanity check" because it supported a systematic and explicit evaluation of the three designs.

The work domain analysis also provided a complementary perspective to the standard evaluation techniques that had been used for evaluating AEW&C designs. First, by focusing evaluation on the functional properties of AEW&C, work domain analysis promoted an understanding of how well the designs fulfilled the work requirements of AEW&C. In contrast, the technical evaluation focused on how well the designs would perform as individual technical units. Second, as the functional properties identified by work domain analysis are event-independent (Vicente, 1999), this approach promoted an understanding of how AEW&C designs would perform in a broad range of situations, including those that cannot be anticipated up front. The operational evaluation, on the other hand, focused evaluation on how the designs would perform in a small range of likely mission scenarios.

In conclusion, we recognize that it may be difficult to convince organizations, with well established policies and practices, to adopt novel approaches like work domain analysis. Therefore, we point out that work domain analysis can be used fruitfully on a smaller scale within a particular project. For example, human factors practitioners could use work domain analysis to conduct a comprehensive evaluation of the human engineering solutions of alternative design proposals. Such bottom-up applications of work domain analysis may help to demonstrate its usefulness to senior managers and decision makers.

6.4 ANALYSIS OF HUMAN-SYSTEM INTEGRATION

In recent years, we have become all too familiar with stories of systems that were designed with little concern for the work of human operators. Thus, one of our key concerns on the AEW&C project was whether the human-system integration (HSI) solutions of competing designs would support the intended activity of AEW&C. Our approach was to develop a description of AEW&C activity that could be used as a background for examining HSI solutions, as details about the designs became available to us (Sanderson & Naikar, 2000).

The framework that we developed for analyzing AEW&C activity—Temporal Coordination Control Task Analysis (TCCTA)—combined the approaches of Rasmussen et al. (1994) and Vicente (1999) for control task analysis, and also included several important extensions. In essence, the TCCTA describes the activity of complex systems in terms of (1) the entire activity context in which control tasks occur; (2) the control tasks themselves, the temporal and logical relations between the control tasks, and the physical and purposive constraints (from the work domain analysis) acting on the control tasks; and (3) the mechanics of the HSI for each control task.

To conduct these analyses for AEW&C, we relied on the same sources of information as for the work domain analysis, namely, various AEW&C-related documents and subject-matter experts. The documents provided general descriptions of the operational role of the AEW&C system, the types of scenarios in which this platform would most likely participate, and the broad responsibilities of crew members. The subject-matter experts made projections of the activity that was necessary by the AEW&C system for it to achieve the goals of the work domain.

6.4.1 AEW&C Activity Context

Figure 6.6 shows that we described the activity context for AEW&C in terms of major classes of work functions (rows) and mission contexts (columns). The major classes of work functions are (1) mission planning and reporting; (2) system setup, configuration, and shutdown, (3) surveillance, and (4) asset control. The major classes of mission contexts are; (1) on ground, not in aircraft; (2) on ground, in aircraft; (3) on way to station; (4) on station; (5) returning to base; (6) on ground, in aircraft; and (7) on ground, not in aircraft.

The activity context for AEW&C captures the concerns of the crew at each phase of mission, and their changing preoccupations as the mission progress-

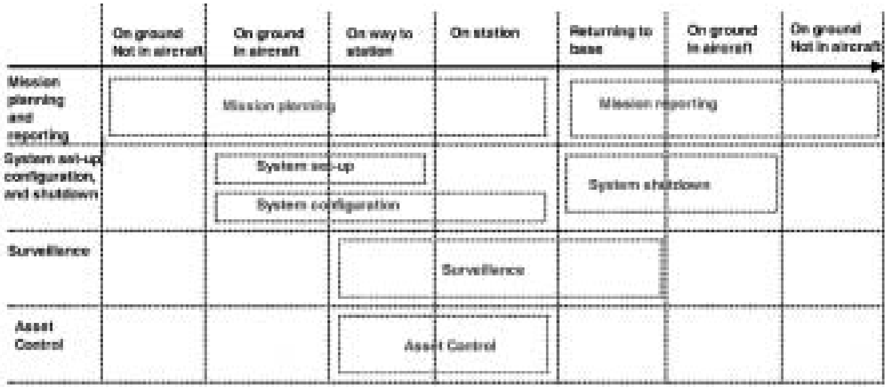


Figure 6.6: The activity context for AEW&C.

es. For example, mission planning is a preoccupation in the earlier phases of a mission, whereas mission reporting becomes a preoccupation at the later stages. In addition, the AEW&C activity context captures the changing background activity against which various control tasks are performed. For example, the background activity for mission planning when "on ground, in aircraft" involves system setup and system configuration control tasks. However, the background activity for mission planning when "on station" involves system configuration, surveillance, and asset control tasks. It is important to look at the entire activity context, and not just single control tasks or clusters of control tasks, because the same control tasks may require different kinds of HSI solutions depending on the context within which the tasks are performed.

6.4.2 AEW&C Control Tasks

Having identified the AEW&C activity context, we then focused on the control tasks that are necessary within that context for achieving the goals of the work domain. Figure 6.7 shows some of the control tasks for the class of surveillance activity for AEW&C; the control tasks are in the shaded boxes. Above each control task, we identified the priorities and values (from the work domain analysis) that the crew members must preserve as they execute the control tasks. Below each control task, we identified the purpose-related functions that the control tasks support or promote. To the right of each control task, we identified the set of actors that might be responsible for executing the control tasks. The connecting arrows illustrate the temporal and logical coordination of control tasks, and the set of initiating conditions for each of the control tasks. However, we are still developing a notation for capturing these types of constraints more effectively.

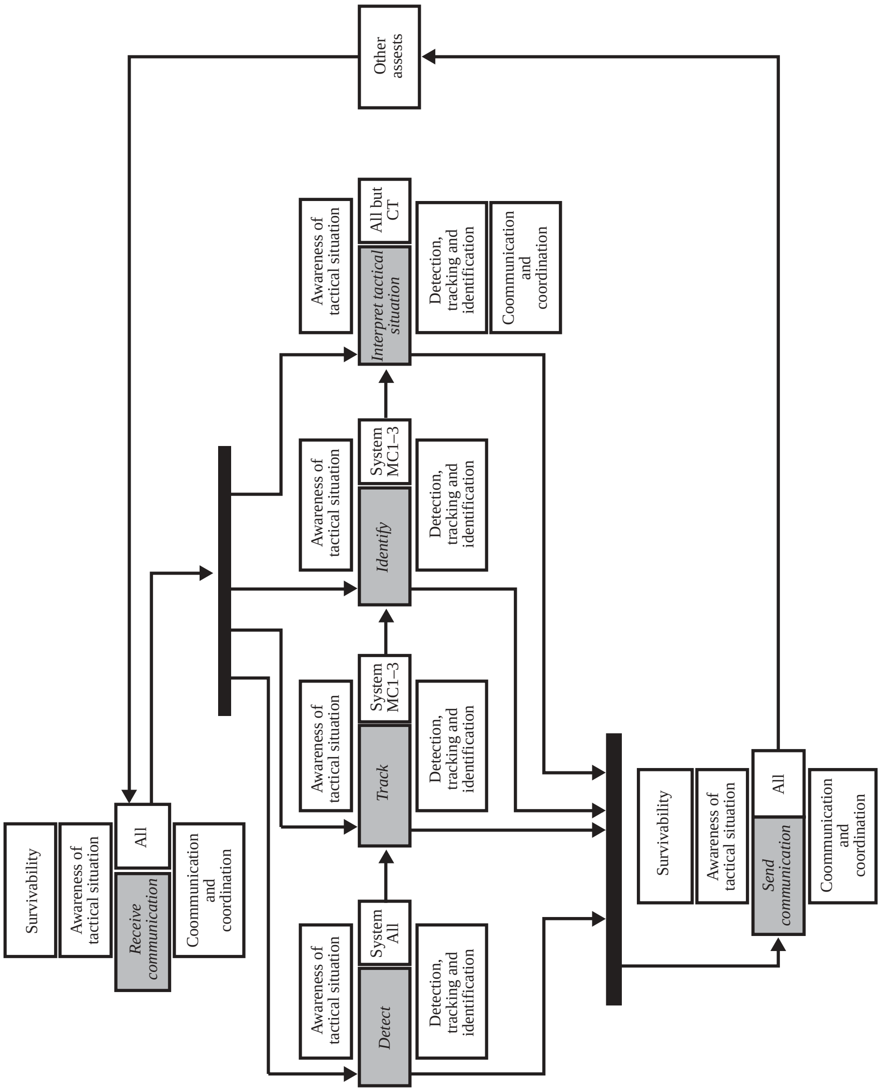


Figure 6.7: Some of the control tasks for the surveillance activity of AEW&C with connections to aspects of the underlying work domain analysis.

6.4.3 AEW&C Human-System Integration

Our third step in describing AEW&C activity was to identify the HSI mechanics for each of the control tasks. On the AEW&C project, our role was that of evaluators rather than designers of the HSI solutions. Thus, to perform this

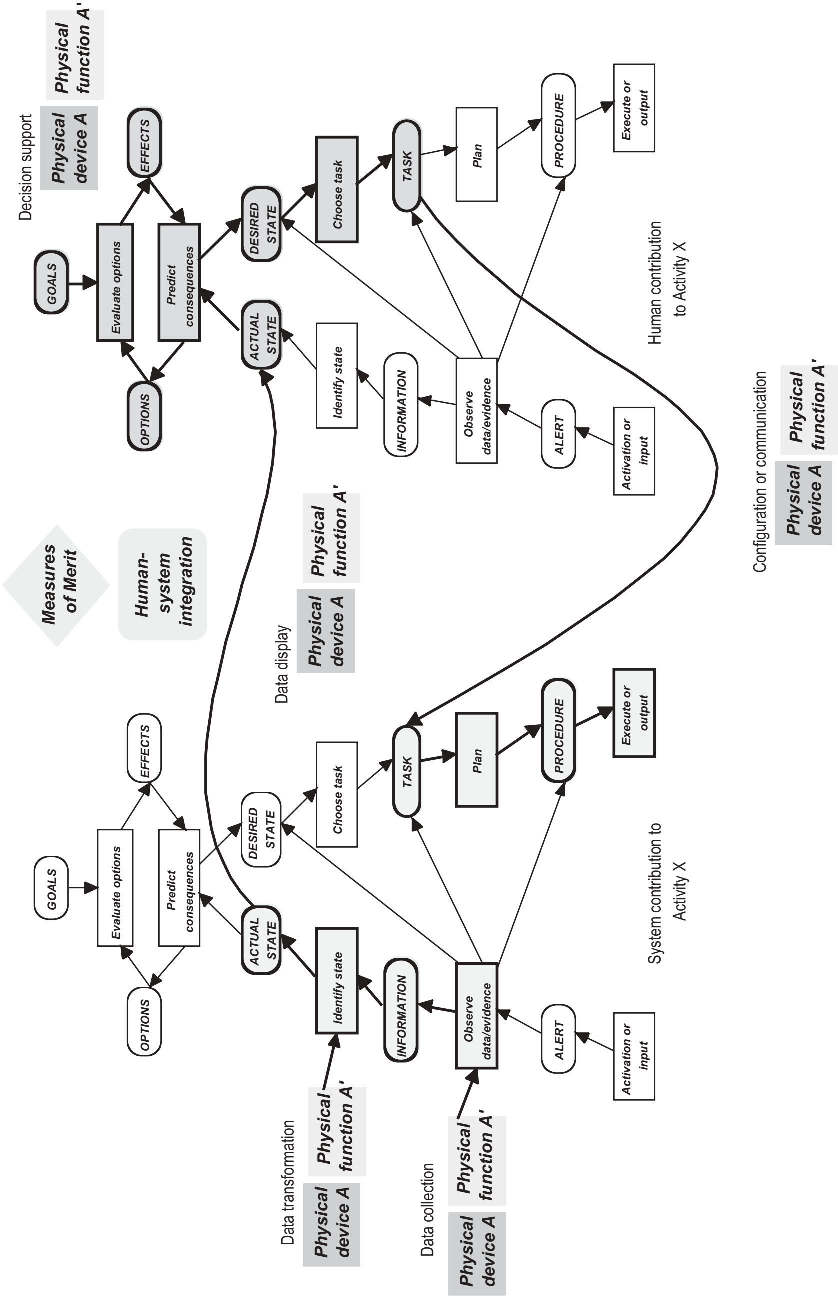


Figure 6.8: Decision ladders linked to show human-system integration.

step we had to rely on the aircraft manufacturers to provide information about their HSI solutions. If the right information was made available, we could then use Rasmussen's decision ladder formalism to illustrate and discriminate the different levels of HSI for each control task.

Figure 6.8 shows a template linking two decision ladders that we used to characterize how the processes of information gathering and analysis, hypothesis testing and generation, and planning and execution were allocated across human and computer in a particular design. We also used the template to indicate the various physical devices and physical functions (from the work domain analysis) that support the information processes shown on the decision ladders. Based on the work of Sheridan and Verplanck (1978), we could then summarize the level of HSI that a particular design offered in the following way:

- HSI Level 1: human performs the whole interpretation or decision action
- HSI Level 2: system generates the options for action or interpretation
- HSI Level 3: system generates options for interpretation or action and suggests best option for human to implement
- HSI Level 4: system generates options for interpretation or action and implements best action if human authorizes
- HSI Level 5: system generates options for interpretation or action, implements best option, and informs humans if requested.

For each control task, the HSI characterization may be at a single fixed level or adaptive over several levels.

Our experience during evaluation was that while there was a lot of information about the physical devices of AEW&C, there was not much information about the integration, cooperation, and communication mechanisms between humans and machines. This information should become available when detailed development of the system begins by Boeing, the winning manufacturer. We expect to use our activity analysis to monitor the development of the HSI solutions as the AEW&C system is developed.

We also note that we have started to use our activity analysis to evaluate alternative crewing concepts and to examine teamwork issues for AEW&C (Naikar, Drumm, Pearce, & Sanderson, 2000). This work involves some aspects of socio-organizational analysis. So far, we have used our models to generate a new team design for AEW&C that subject-matter experts think is promising. This team design will be evaluated in future research.

6.5 TRAINING-SYSTEM DESIGN

Our interest in using work domain analysis for training-system design has been stimulated by a number of concerns. One concern is that transfer-of-training

Functional Structure	Training Needs	Functional Requirements
Functional Purposes: why a work domain exists or the reasons for its design	*Training Objectives:* purpose for training workers is to fulfill the function purposes of a work domain	*Design Objectives:* training system must be designed to satisfy the training objectives of the work domain
Priorities and Values: criteria for ensuring that purpose-related function satisfy systen objectives	*Measures of Performance:* criteria for evaluating trainee performance or the effectiveness of training programs	*Data Collection:* training system must be capable of collecting data related to measures of performance
Purpose-related Functions: functions that must be executed and coordinated	*Basic Training Functions:* functions that workers must be competent in executing and coordinating	*Scenario Generation:* training system must be capable of generating scenarios for practising basic training functions
Physical Functions: functionality afforded by physical devices in the work domain and significant environmental conditions	*Physical Functionality:* workers must be trained to exploit the functionality of physical devices and operate under various environmental conditions	*Physical Functionality:* training systems must simulate the functionality of physical devices and significant environmental conditions
Physical Form: physical devices of the work domain and significant environmental features	*Physical Context:* workers must be trained to recognise functionally-relevant properties of physical devices and significant environmental features	*Physical Attributes:* training system must recreate functionally-relevant properties of physical devices and significant features of the environment

Figure 6.9: Connection between the functional structure of a work domain, training needs, and the functional requirements of training systems.

research has generally failed to show strong transfer from training devices to operational systems. This led us to wonder if the normal way of identifying training requirements is flawed. In addition, there is a recurring concern in training-system design with issues of fidelity. Designers of training systems have become well aware that something other than physical fidelity must be used to guide design decisions. The concept of functional fidelity has been promoted. However, there has been no principled method of distinguishing functional from non-functional fidelity. As work domain analysis is explicitly designed to identify and map the functional constraints of a work system, it seemed that this framework might be used to identify those characteristics of a training system that encompass functional fidelity.

Figure 6.9 shows how we have used work domain analysis for transforming the functional structure of a work domain into functional properties to recreate in a training system. By the use of this framework, each layer of the abstraction hierarchy is translated into particular kinds of training needs, which is then translated into particular kinds of functional requirements for training systems (Naikar & Sanderson, 1999).

Other uses of this framework include tracing the impact of leaving out parts of the functional structure of a work domain from a training device (Lintern & Naikar, 2000). For example, if the attributes of physical form B are

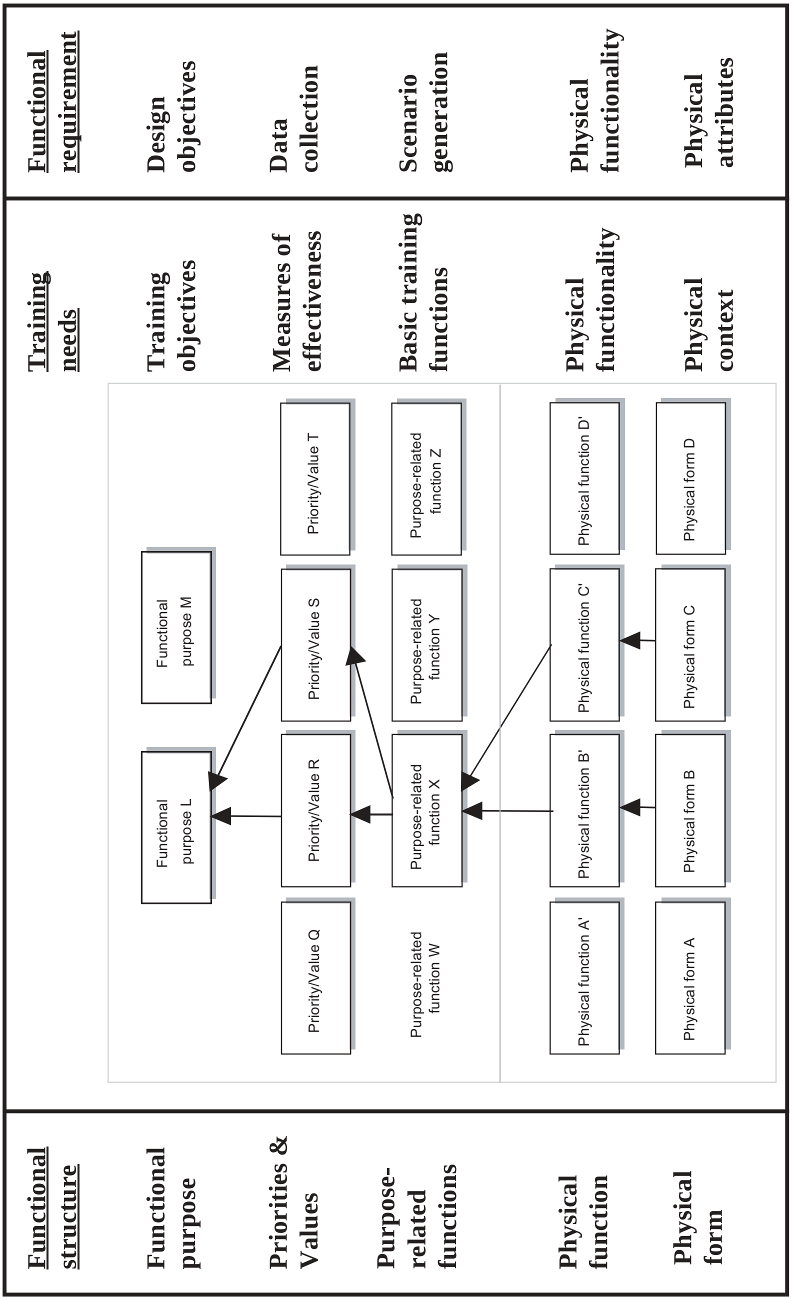


Figure 6.10: The abstraction hierarchy offers a means for tracing the impact of various design decisions on training.

not recreated in a training-system, we can use the links in the abstraction hierarchy to determine the impact this would have on training workers to perform higher-level functions (Figure 6.10). Moreover, work domain analysis can also be used to identify the requirements for part-task training. For example, in designing a part-task trainer for purpose-related function X, we could use work domain analysis to identify the functional relationships that must be present in a training device to support training of that function.

At DSTO we have used work domain analysis to help the Australian Defence Force in purchasing a training system for F/A–18 pilots. As the F/A–18 aircraft is currently undergoing a major system upgrade, our job was to identify the training needs of pilots and the functional requirements for a training system for the up-graded aircraft. To conduct the F/A–18 work domain analysis we used various tactical, training, and flight manuals, and input from subject matter experts. Figure 6.11 shows (1) a global view of the F/A–18 abstraction hierarchy, and (2) a sample of functions from each layer of the abstraction hierarchy. A detailed description of how this framework was used to identify the training needs of F/A–18 pilots, and the functional requirements for a suitable training system can be found in Naikar and Sanderson (1999).

6.5.1 Training Objectives and Design Objectives

The functional purposes layer of the F/A–18 abstraction hierarchy lays out the training objectives of the F/A–18 work domain and the design objectives for a suitable training system. Figure 6.11(b) illustrates that the ultimate goal of training F/A–18 pilots is to ensure the security of sovereign airspace and to maintain the initiative for offensive action. In turn, in designing a training system for this work domain, the goal is to develop a device that supports the training objectives of the F/A–18 work domain.

6.5.2 Measures of Effectiveness and Data Collection

The priorities and values of the F/A–18 work domain describe measures of effectiveness for evaluating trainee performance, and the data collection requirements for an F/A–18 training system. For example, on strike missions, we need to evaluate whether F/A–18 pilots degraded the combat effectiveness of the enemy, whether they caused unnecessary or excessive damage, and whether the pilot operated within procedural constraints (e.g., rules of engagement) and physical constraints (e.g., time, distance, fuel). Thus, the data collection capabilities of a training system must be suitable for capturing this type of information.

We can also measure trainee performance at levels lower than the priorities and values layer of the abstraction hierarchy (Lintern & Naikar, 2000). For

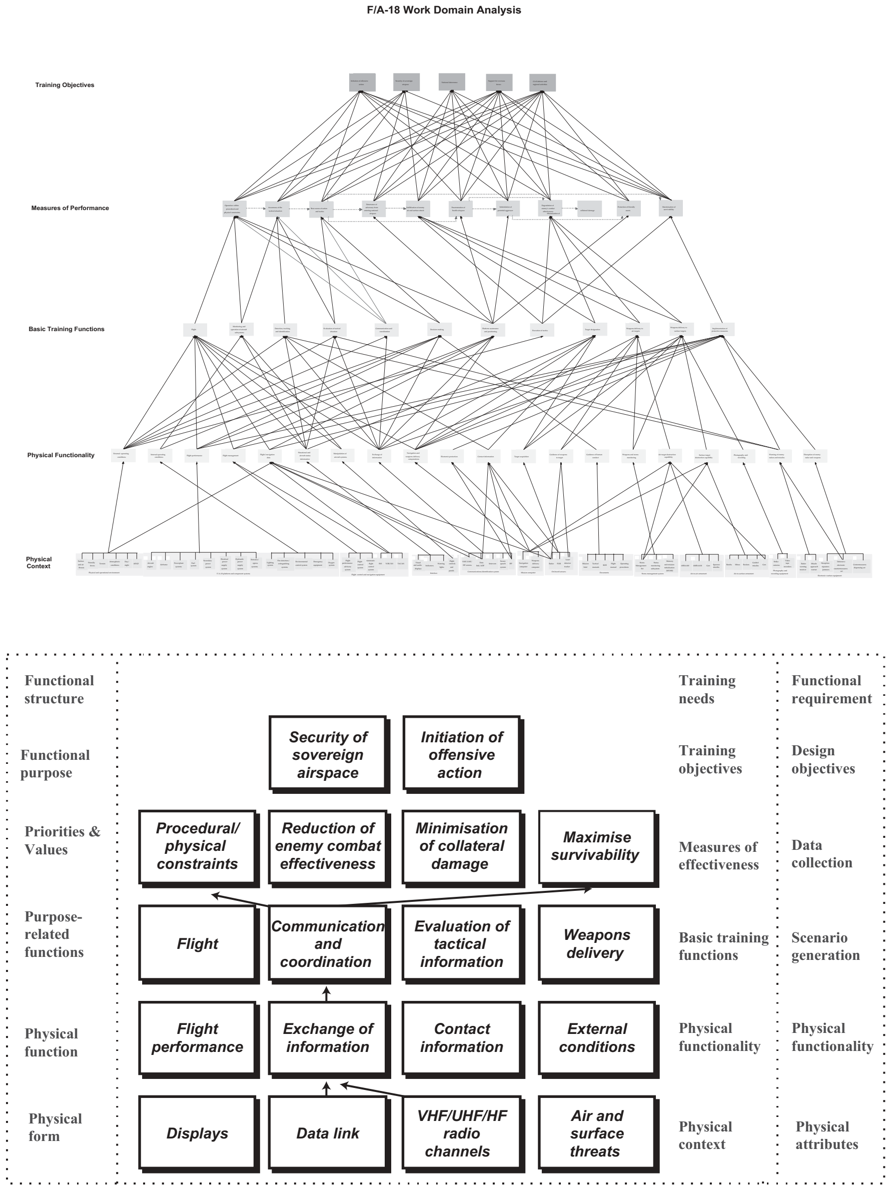


Figure 6.11: (a) A global view of the F/A–18 abstraction hierarchy. (b) A sample of functions from each layer of the F/A–18 abstraction hierarchy.

example, we may want to measure whether F/A–18 pilots control various aircraft subsystems appropriately (physical form layer), or we may want to measure the accuracy of weapons delivery in terms of distance from target (purpose-related functions layer). Although these measures do not relate directly to the essential priorities and values of the F/A–18 work domain, they do provide diagnostic indices of pilot performance.

6.5.3 Basic Training Functions and Scenario Generation

The purpose-related functions of the F/A–18 work domain inform the basic training functions of F/A–18 pilots and the scenario-generation requirements for a training system. Thus, Figure 6.11 shows that in training F/A–18 pilots we must be concerned not only with flight and weapons delivery, as is typical of many fighter-pilot training programs, but also with communication and coordination, and evaluation of tactical information. Thus, from this layer of the abstraction hierarchy, we can derive the capabilities for scenario generation that a training device must have to support the F/A–18 training program.

Although we have promoted the purpose-related functions layer as the defining layer for the basic training functions of a work domain, the goal of training should be to teach students to exploit all possible means for realizing a target function (Lintern & Naikar, 2000). So, for example, F/A–18 pilots should be trained to reach the target function of communication and coordination via voice channels, data link, and by signaling with the airframe (e.g., tilting the wings of the aircraft). In addition, F/A–18 pilots should also be trained in the effects that their actions at one level can have on higher-level functions (Lintern & Naikar, 2000). For instance, by communicating new rules of engagement to a wingman via radio channels, a pilot may be compromising his survivability as the radio transmissions from his aircraft may be noticed by an enemy pilot. We can use the means-ends relations of an abstraction hierarchy to develop a comprehensive statement of the scenario generation requirements of a training system.

6.5.4 Physical Functions

The physical functions layer of the F/A–18 abstraction hierarchy reflects that pilots must be proficient at manipulating the functionality of aircraft subsystems, and also at operating under different external conditions. For example, Figure 6.11 illustrates that F/A–18 pilots must be proficient at manipulating the flight performance characteristics of the aircraft, and operating under different weather conditions and levels of hostility. Thus, the fourth layer of the abstraction hierarchy conveys the physical functions to recreate in a training system to support training of higher-level functions.

6.5.5 Physical Context and Physical Attributes

The physical context for training F/A–18 pilots and the physical attributes of training systems are reflected in the final layer of the abstraction hierarchy. For example, F/A–18 pilots must be competent at operating different kind of physical devices, such as visual displays and data link. In addition, they should be capable of recognizing different features of the external environment, such as terrain and types of air and surface threats. Thus, a training system for F/A–18 pilots must recreate these physical properties.

Recently, the Australian Defence Force released parts of the F/A–18 work domain analysis to potential manufacturers for the F/A–18 training system. In time, the F/A–18 work domain analysis will form the basis for a detailed design specification of the F/A–18 training device. However, preliminary work has shown that to fully complete the specification for this system, we will need to go beyond work domain analysis. Lintern and Naikar (2000) describe the following areas as requiring alternative forms of analysis: (1) critical skills to emphasize in training, (2) the form in which to implement particular functional requirements, (3) the levels and types of fidelity of various physical components, and (4) special features for supporting instruction. These additional requirements are not limited to work domain analysis but are necessary even if one adopts more conventional approaches to training-system design.

Our experience in using work domain analysis for training-system design is that this framework offers several advantages over more conventional techniques. One advantage is that by using work domain analysis we can derive the functional requirements for training systems directly from the functional structure of the work domain itself. In contrast, Instructional Systems Design (ISD) focuses on identifying typical tasks or procedures that will be trained with the new device. Once this analysis is complete, an additional step is required to go from the description of tasks to a description of functional requirements. This step is most often done informally and task by task.

Another advantage of work domain analysis is its suitability for specifying training devices that are not yet operational. For brand new combat systems, or for combat systems that are being upgraded, it is difficult to fully anticipate training requirements. Workers will find new ways of using the platform as they develop expertise with it, and ways of using the platform will also be influenced by the capability of future enemy systems. Conventional techniques cannot inform the design of training systems for these types of events, as it is difficult to develop descriptions of tasks and procedures for ways of using a plat-

Purpose of Analysis	Properties of the Information-Action Workspace	Tools	
		Knowledge Acquisition	**Knowledge Representation**
Work Domain	Physical & Purposive Constraints	Document Analysis Reviews by Subject Matter Experts	Abstraction-Decomposition Matrix
Activities	What needs to be done in the Work Domain (Work Functions & Control Tasks)	Cognitive Walk-Through, Study of Work Practices	Decision Ladder
Strategies	Strategies for Management & Control (Planning, Adapting)	Critical Decision Methods, Interaction Analysis, Verbal Protocol Analysis	Information Flow Map
Social-Organisational	Collaborating Actors & Organisational Structure	Communications Analysis, Interaction Analysis	Integrate information from tools above
Concepts & Competencies	Human Capabilities & Limitations (SRK, Conceptual Distinctions)	Repertory Grid Analysis & Review of Decision Ladder	Concept Map & Skills-Rules-Knowledge Frame

Figure 6.12: A set of tools used for knowledge acquisition and knowledge representation in each phase of a cognitive work analysis for identifying the design-relevant properties of an information-action workspace. The tools shown here illustrate how it is possible to proceed with a cognitive work analysis. However, the diversity of tools that is available is too great for this figure. Different tools could be substituted with good effect, depending on the demands of the project and the expertise of the analysts (Seamster, Redding, & Kaempf, 1997; Lintern, in press).

form that are not yet known. Work domain analysis, however, avoids this problem by focusing on event-independent properties of a work domain.

6.6 INFORMATION WORK SPACES

It is said that we live in the information age. Although information has always been critical to human action, it sometimes seems that our modern society has overburdened us with information. We do, in fact, function quite well with a relatively small amount of information if that information is relevant, timely, and organized to suit our natural capabilities of perception, interpretation, and action. Where we are overburdened with information or are unable to make good decisions, it is primarily because information is poorly organized, fragmented, or pitched at a level of abstraction that does not link directly into the

Level of Abstraction	**Representation Requirements**	**Formats**
Functional Purposes		
Priorities and Values	Flow Mass Value Balance Accumulation Dispersion	Configural Displays of Balances & Relationships Between Functions & States Limit Envelopes
General Functions	Relations Intended States Trajectories Offensive Capability Defensive Capability	Configural Displays Constraint Boundaries Threat & Lethality Shadows Guides Predictor Elements & Envelopes Symbolic Diagrams Target Lists Priority Indicators
Physical Functions	Status of process variables with reference to target states and to limits of acceptable operation	
Physical Form	Topography of the work system	Object Representations Icons, Symbols, Signs Mimic Diagrams Pictorial Representations Flow Maps Ingress & Egress Routes Locations Fields of Action

Figure 6.13: A typology of display formats for different levels of abstraction. (Adapted primarily from Rasmussen, 1998; but also with reference to Dinadis & Vicente, 1999; and to Pejtersen, 1992).

functional interpretation-action sequence. What is needed is an appropriately configured functional interface (Lintern, Waite, & Talleur, 1999).

Following the lead of Pejtersen (1992) in her design of an interface for a children's library, we have proposed to use CWA as the analytic method for accomplishing much of the early conceptualization for the design of an information system (Figure 6.12). Work domain analysis identifies the functional requirements that must be made visible at the interface, and activity analysis identifies what needs to be done in the work domain. strategies analysis identifies how the operator can interact with this system. For an information workspace, the primary product of the strategies analysis is a map that shows what information is needed and how it flows through the work system.

Our area of concern is military command and control, which is quite a different form of information system from a children's library. Nevertheless, the conceptual challenges to the designers of the information interfaces are similar, as are the representation requirements and the display formats that might be useful. Thus the tools for knowledge acquisition and knowledge representation should also be similar (Figure 6.13). At this stage, these ideas remain conceptual (Lintern & Naikar, in preparation) but we propose to test them in the development of a command and control information space. The aim is to integrate forms for perception and action into a virtual workspace in a manner that will support access to essential information and that will provide means for testing and implementing decisions.

6.7 CONCLUSIONS

In our work in air defense contexts over the last two years, we have used CWA for many purposes other than interface design, such as specification of training programs, specification of simulator needs, design of research programs, intelligent agent modeling, and evaluation of design solutions, and we have found that CWA provides significant insight (see Sanderson et al., 1999 for applications not discussed in this paper). We have also found that the products of CWA have been reusable across many different purposes. Consequently, CWA has become an intellectual framework for certain groups within DSTO, where human factors practitioners, training specialists, simulator constructors, cognitive scientists, and operations researchers can communicate and dovetail their activities.

There is considerable effort involved in performing CWA, and some of the conceptual material the analyst needs to understand to do it properly has subtle but critical differences from more familiar approaches to human engineering. However, we suggest that CWA provides an approach to human engineering that is no more complex than what has been suggested in more traditional human engineering programs and may actually be simpler. Not only are the five phases of CWA tightly linked, but also the products of the analyses can be reused in the ways described above. We therefore look forward to seeing how the cells in Figure 6.3 are populated as cognitive engineers gain experience with CWA over the next few years.

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