USE OF COGNITIVE WORK ANALYSIS ACROSS THE SYSTEM LIFE CYCLE: FROM REQUIREMENTS TO DECOMMISSIONING

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Cognitive Work Analysis (CWA) is a systems-based approach to the analysis, modelling, and design of complex sociotechnical systems that is particularly useful when working with real-time work domains in which operator adaptation and flexibility may be needed (Rasmussen, Pejtersen, & Goodstein, 1994; Vicente, 1999). In this paper we argue that CWA can be used not only for design, with which it is most commonly associated, but also throughout the system life cycle. We present a table that shows the five phases of CWA crossed with different steps and activities in the system life cycle, and in the cells of the table we indicate how a particular phase of CWA informs the system life cycle activity in question. We illustrate this discussion with material from our own work using CWA in air defence environments, such as the use of work domain analysis in the tender evaluation for Australia's AEW&C system. CWA not only leverages and coordinates some previous human engineering techniques, but it also adds important analytic products that have been absent from previous techniques.

INTRODUCTION

Cognitive Work Analysis (CWA) is a systems-based approach to the analysis, modelling, design, and evaluation of complex sociotechnical systems that has its foundations in the work of Jens Rasmussen at Riso National Laboratories (Rasmussen, 1986; Rasmussen, Pejtersen, & Goodstein, 1994). Its focus is complex, real-time work domains in which operator adaptation and flexibility is needed if the negative consequences of unanticipated situations are to be avoided. We can support operator adaptation and flexibility if we design systems that are based not on supporting typical or normal work trajectories, such as specific sequences of actions, but instead based on models of the constraints and possibilities for functional action (affordances) in the work domain. If the computer-based interface to a complex work domain is designed so that operators can see the constraints, boundaries, and affordances of that work domain, then they are much more likely to respond appropriately if something unusual happens. Rasmussen has referred to this as the human operator "finishing the design" of the system. Provided with many degrees of freedom for action, the operator can choose actions that preserve the functional purpose of the system. CWA has been given a great stimulus in Vicente's (1999) recent text which describes, in the clearest terms to date, the conceptual foundations and modelling tools of CWA.

The goal of the present paper is to show that CWA can be used at all points in the system life-cycle, rather than just for system design. Although many researchers and human factors professionals have commented that carrying out a full CWA is a daunting task, we argue that CWA is probably less effortful than many currently-recommended human factors techniques. Moreover, the results of CWA modelling efforts can be put to multiple uses throughout the system life cycle, so offering a huge potential for re-use. They can also probably be put to more general uses than is possible with conventional human factors techniques. Because some authors of this paper are employees in the defence industry, our perspective is that of military and particularly air defence systems. However our conclusions extend to industrial and commercial systems.

In the sections that follow, we first give an overview of the modelling steps of CWA. Then we provide a framework for thinking about the impact of CWA throughout the system life cycle, providing some examples of our own use of CWA in contexts other than system design. Finally, we consider the workload involved in doing CWA.

THE CWA FRAMEWORK AND ITS VARIANTS

Figure 1 is an amalgamation of figures used by Rasmussen et al., (1994) and Vicente (1999) to make the point that there are many factors that impose constraints on the activity that is possible within a certain work domain, while at the same time opening out possibilities for action. Activity, seen in the centre, is better described by the constraints and affordances that influence activity than by sequences of actions. Around the edges of this diagram Rasmussen et al. (1994) identify eight factors that shape action. These eight factors can be cross-classified according to whether they are talking about the definition of *activities* (what must get done, why, with what, and how) or the definition of *actors* (who gets things done and with whom), and whether they are talking about *environmental* constraints (imposed by the broader context of work) or *cognitive* constraints (imposed by the nature of individual actors).

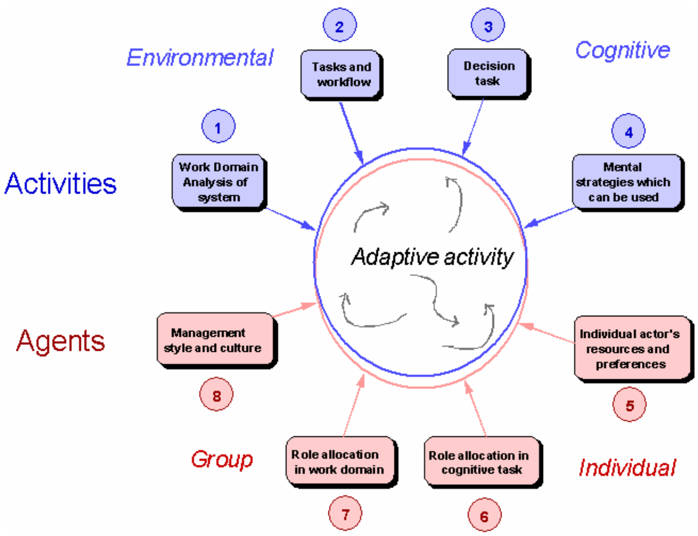


Figure 1: Factors that contribute to adaptive activity by human operators in complex sociotechnical systems.

In the actual modelling work of CWA, the eight factors identified in Figure 1 are usually reduced to five phases of analysis (Rasmussen et al., 1994; Vicente, 1999) which are shown in Figure 2. In Figure 2 is a graphical icon to illustrate the kinds of modelling tools used in each phase of CWA.

Work domain analysis (WDA) involves modelling the physical and purposive properties of the system in which activity will take place. It is shown in node 1 of Figure 2. The abstraction-decomposition space is the modelling framework used. WDA is independent of any events or actions.

Control task analysis (CTA) is a statement of the control tasks that must take happen for activity to occur in the work domain. It is an amalgamation of nodes 2 and 3 of Figure 2. The decision ladder is often used.

Strategies analysis refers to the different strategies that might be used to carry out a control task. It is shown in node 4 of Figure 1. Examples are decision flow charts.

Social-organisational analysis refers to who carries out work and how it is shared. It is an amalgamation of nodes 6 and 7 of Figure 1. It involves partitioning or annotating other diagrams to show the actor.

Competencies analysis refers to workers' knowledge, training, capabilities, and expertise. It is shown in node 5 of Figure 1 and is represented usually in the skill- rule- and knowledge-based behaviour distinction of Rasmussen (1986).

CWA AND THE SYSTEM LIFE-CYCLE

Because of the focus on using CWA for system design, particularly in light of the role that the first three phases play in Ecological Interface Design (Vicente & Rasmussen, 1992), there has been a tendency to overlook the use of CWA for other purposes than interface design. Yet a strong case can be made for CWA's usefulness at all points in the system life-cycle, from requirements to decommissioning.

Figure 3 shows the five phases of CWA in its columns and various kinds of activities at different stages in the system life-cycle in its rows. Cells describe how the products of CWA modelling 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 others 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 system development activity indicated. Further use of CWA across different contexts will flesh out this table with practical examples.

In the following paragraphs we briefly go through the system lifecycle activities listed and outline how CWA might inform each stage. In some cases, where we have found CWA particularly useful, we provide brief details of our activities.

Requirements. WDA gives us a framework for developing requirements by thinking about why a new system should exist, what its environmental context will be, and what functions it should implement. From there, physical requirements can be determined. In some cases, physical requirements are already given in a customer's requirements statement. WDA provides a framework to put these in context. Although requirements may indeed emerge from the activity seen in legacy systems, the contribution of CWA is to support the development of revolutionary systems unconstrained by previous solutions, rather than of just evolutionary systems.

Specification. In a specifications stage, more detail is needed for design to proceed. A system developer needs to know what must be done in the work domain for the system to achieve its functional purpose. Therefore, the knowledge about activity that a control task analysis provides is an important contributor to building specifications for the system. Further detail is filled in during detailed design, as outlined in the next paragraph.

Design. Following Vicente (1999), design has been classified into five general stages that reflect what each of the five phases of CWA offers. Definition of hardware and software needs, (models, databases, sensors, etc) needs can be described in a WDA, even though it may be guided by information from other phases.

Phases of Analysis	Kinds of Information	Modelling Formalisms
Work Domain Analysis	Purpose and structure of work domain	Abstraction-decomposition diagrams Abstraction hierarchies
Activity 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
Competencies Analysis	Kinds of mental processing supported	Skills, Rules, and Knowledge models

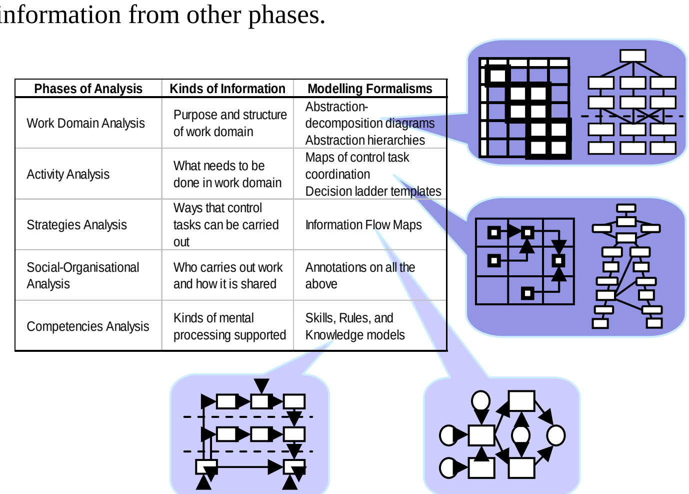


Figure 2: Five phases of Cognitive Work Analysis discussed in Vicente (1999).

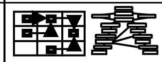
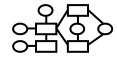
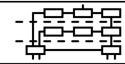
Phase of CWA:	WDA	Activ A	Strat A	Soc/Org A	Comp A
				*Annotation of other diagrams*	
	Purpose and structure	Control tasks and coordination	How control tasks carried out	Who does what and with whom	Mental processes entailed (SRK)
Requirements	develop				
Specifications	develop	develop			
Design					
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 3. The contribution of different phases in CWA to activities and needs at different points in the system life-cycle.

In order to define control tasks we need to know what the work domain is (thus "given" under WDA). In order to define effective strategies for carrying out control tasks we need to know what those control tasks are (thus "given"). In order to define job roles, responsibilities, allocation of function, and coordination structures, effective strategies should already be determined (thus "given"). Finally, to define the format of interfaces and visual displays, the actor responsible for control tasks to be supported by the interface should be "given."

Simulation. Simulation takes several forms. First, it refers to the development of full- or part-scale simulators of the system being developed to support training, further system development, etc. All phases of CWA contribute to simulation. For example, Naikar and Sanderson (1999) have shown that WDA provides a framework for defining the requirements of large-scale simulators that will support effective training environments (see also below under "operator training"). Second, simulation refers to modelling events and the system's response to events. Using a BDI (beliefs, desires, intentionality) framework for modelling the activities of intelligent agents, Goss and Heinze (in Sanderson & Naikar, 1999) have shown that WDA can describe the purposive and physical environment of intelligent agents and the decision ladder (used in CTA) can provide a template for modelling the decisions of intelligent agents (see Figure 4). This opens the possibility of simulation operationalizing a WDA structure

Evaluation of designs. CWA provides us with tools for characterising, comparing, and evaluating different designs during the development of a system. Ideally we would proceed with a complete description of the proposed system, but in reality this is impractical.

CWA can be a very powerful tool for evaluating different design proposals. WDA has a unique "summarising" role in this respect. Acquisition and procurement processes tend to focus on whether technical and physical requirements have been met. The focus is therefore very much at the physical function level of WDA and whether a proposed design complies with a great many physical requirements. The connection of physical functions with the purpose, priorities, and field of operations of the system is not explicitly spelled out. WDA provides a framework to make the connection explicit and so helps to determine whether a proposed design will lead to a system that fulfils its functional purpose or whether it will fail, and if so, why.

Figure 5 illustrates this with a generic abstraction hierarchy, where physical functions B and C are both used to achieve purpose-related function Z. It may be that the proposed design solutions for physical functions B and C, when taken alone, may satisfy physical performance requirements, but when put together may make it very different to perform purpose-related function Z. In turn, once purpose-related function Z is compromised, the ability to conform to a key priority or a key value of the system, such as priority value W, may also be compromised.

One of the major challenges in the acquisition of complex systems is determining which of several design proposals will best fulfil the military purposes for which the proposed system is intended. However, current tender evaluation practices, which focus on the technical and performance requirements of various physical subsystems of the platform (Department of Defence, 1995), do not explicitly take into account the work domain or the context in which the system will be used; factors which can affect system performance and safety (Vicente, 1999). Although, in some cases, the results at the level of physical subsystems are evaluated against specific mission tasks (Gabb & Henderson, 1996), the tasks are typically those that can be anticipated by workers and systems analysts. Hence, little can be ascertained about the performance of the system under novel or unpredictable conditions.

By identifying the functional constraints of a work domain, which are independent of particular circumstances, work domain analysis provides a framework for tender evaluation that is able to accommodate a large number of system responses to both routine and unpredictable situations.

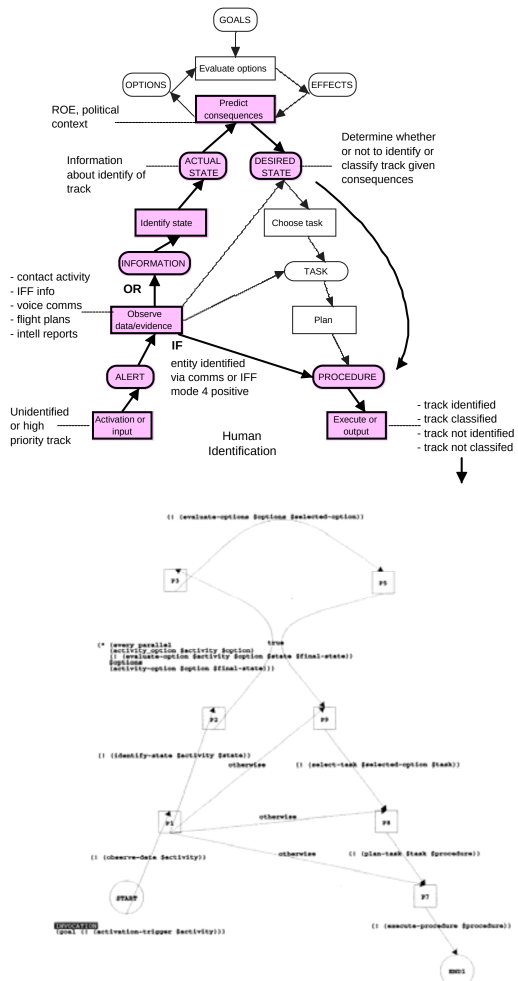


Figure 4. Decision ladder of agent decisionmaking used as a template for a BDI-based simulation environment for multiple cooperating intelligent agents in an air defense context.

This approach was used to support the acquisition of an Airborne Early Warning and Control (AEW&C) system for the Australian Defence Forces. Specifically, the purpose-related constraints of the AEW&C system were used to derive a set of mission functions against which the performance and technical solutions of alternative design proposals were evaluated. Such a framework moved tender evaluation beyond a focus on physical subsystems to whether the design solutions would fulfil the functions of the AEW&C work domain, under both routine and unpredictable conditions.

Implementation. CWA has the potential to guide the implementation process. In particular, WDA captures structural and functional groupings of elements that might be worth implementing together so that a more effective testing procedure can take place.

Test. As implementation proceeds, CWA can guide the testing process. This will be particularly effective if a simulator is available, either in part or in full. WDA has an important role to play here. Groupings of functions and physical elements, at their present stage of development, can be tested in terms of whether they achieve their collective ends (the abstraction dimension of WDA), and whether they function effectively as wholes (the aggregation dimension of WDA). WDA, then, allows testing of whether the work domain emerging from implementation matches the WDA as initially drawn up. The WDA helps us determine figures of merit appropriate to the description of the system at different levels of abstraction. Similarly, whether control tasks, strategies, role allocation and coordination structure, and operator cognitive capabilities are being supported can also be tested to the extent that a simulator or field context makes possible.

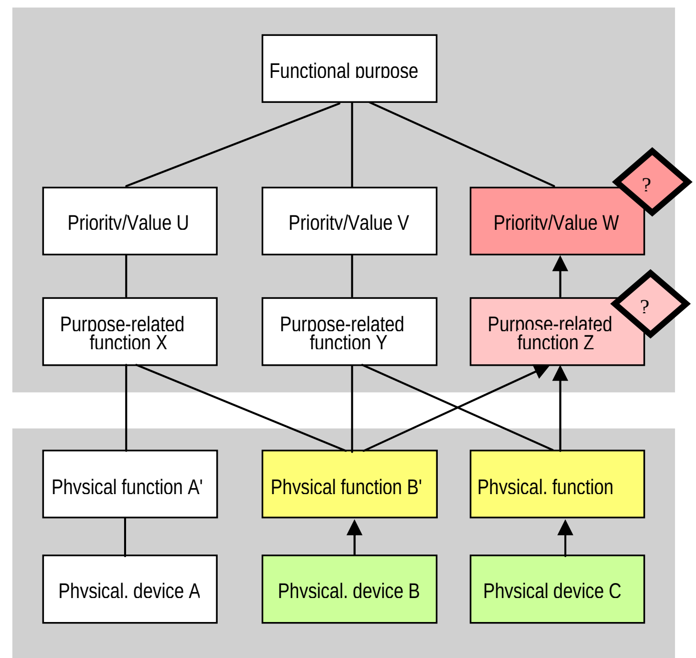


Figure 5. WDA framework for evaluation of system design. Will physical functions work together to achieve purpose-related functions (lower diamond)? Will purpose-related functions work together to satisfy priorities (upper diamond)?

Operator selection. Operator selection can be guided by the definition of actor roles given during the design phase, and the definition of actor competencies implied by interface formats. Requirements for operator competencies in turn inform the structuring of operator training.

Operator training. As Lintern and Naikar (1998), Naikar and Sanderson (1999), and Naikar, Sanderson, and Lintern (1999) have pointed out, CWA can inform training in powerful ways that focus more on finding ways to satisfy the functional purpose of the work domain in different ways than on drill in procedures. As for the Testing stage of the system life cycle, levels of abstraction in the WDA suggest different figures of merit for effective operator action.

Routine, non-routine, and maintenance activity. CWA can be used to describe routine, non-routine, and maintenance activity within a system. Indeed, much of Rasmussen's work while developing the modelling 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 modelling, 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.

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, display design, communications procedures, etc. We have achieved this by embedding control tasks in a coordination structure that represents activity in work domain terms (Rasmussen et al., 1994) and by dividing the coordination structure into principal phases of operation, or instantiations of the work domain. This gives us a profile of the control tasks within a phase of operation, the temporal, logical, and structural coordination between those tasks. This sketches the “ecology” of the work environment: the activities to be performed and their temporal distribution, the purposes being pursued, the physical equipment being used, and so on.

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 anaesthesia environment, Benda and Sanderson (1999) have demonstrated that both WDA and CTA can be extended to show how changes in physical devices and physical functioning create new constraints in or affordances for control task 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 perioperative events.

System retirement. Finally, we envisage that CWA could be helpful in making the decision to retire or decommission a system. A WDA 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. There may be shortfall in the relevance or effectiveness with which the control tasks are carried out.

CONCLUSIONS

In our work in air defence contexts over the last year, we have used CWA for many purposes other than system design, such as specification of training programs, specification of simulator needs, design of research programs, intelligent agent modelling, and evaluation of design solutions, and have found that CWA provides significant insight. We have found that the products of CWA modelling for a domain have been reusable across different purposes (see rows of Figure 3). CWA is becoming 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 in order to do it properly has subtle but critical differences from more familiar approaches to human engineering. However, cognitive engineers and human factors professionals might take heart in the fact that CWA products appear to be readily reusable for wider purposes. Moreover, tools like the Work Domain Analysis Workbench are under development to support and speed some of the phases of CWA (Sanderson, Eggleston, Skilton, & Cameron, 1999).

In light of these factors we suggest that CWA provides an approach to human engineering that is no more complex that what has been suggested in more traditional human engineering programs—such as the procedure recommended by the Air Standardization Coordinating Committee in its recommendations for the application of human engineering to advanced aircrew systems—and may actually be simpler. Not only are the five phases of CWA tightly linked, but also the products of analyses can be reused in the ways described above. We therefore look forward to seeing how the cells in Figure 2 are populated as cognitive engineers gain experience with CWA over the next few years.

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