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Chapter VIII

Cognitive work analysis across the system life-cycle: Achievements, challenges and prospects in aviation

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Introduction

Although technical systems such as aircraft are becoming increasingly automated and their hardware components increasingly reliable, human operators are retained to ensure smooth operation in the face of "normal" disturbances and to handle unanticipated situations. Many human factors techniques indicate how to provide support for human monitoring and intervention under normal disturbances, but few techniques indicate how to support the human operator when a system such as a flight management system encounters extraordinary conditions that have not been anticipated during design.

Cognitive work analysis (CWA) is an approach to analysing, modelling, designing and evaluating complex systems. Proponents of CWA claim that it leads to designs that are particularly useful when people have to adapt to unanticipated situations (Rasmussen, Pejtersen, & Goodstein, 1994; Vicente, 1999). CWA does not focus on how human-system interaction should proceed (normative modelling) or how human-system interaction currently works (descriptive modelling). Instead, it focuses on identifying properties of the work environment and of the workers themselves that define possible boundaries on the ways that human-system interaction might reasonably proceed, without explicitly identifying specific sequences of actions (formative modelling).

From 1998 onwards, researchers at Swinburne Computer Human Interaction Laboratory (SCHIL) and the Defence Science and Technology Organisation (DSTO) have used some aspects of CWA in a variety of work domains, including air defence, anaesthesia, intensive care, and continuous process control. We have applied CWA to problems at different points in the system life cycle, including tender evaluation, instrumentation engineering, definition of crewing needs in C2 environments, training needs, visual and auditory display design, and forecasting the impact of new technologies on work domains (Naikar, Lintern & Sanderson, 2002). Others have applied it to visual display design, including the design of cockpit displays for the C130J (Dinadis & Vicente, 1999).

In this paper we provide some examples of CWA in use in aviation domains from our investigations. We then borrow some ideas from Lakatos (1974) and Chalmers (1982) to assess the effectiveness of CWA. From our experience, we indicate where CWA is likely to be most beneficial, where its strengths and weaknesses appear to lie, and what the prospects are for its future development and use.

Overview of Cognitive Work Analysis

CWA orients the analyst towards five different factors that need to be taken into account when analysing human work in complex sociotechnical systems such as an air defence environment, the cockpit, or an ATC environment. Each factor captures a different, but important set of considerations that will affect what kind of human activity is possible and sensible. Figure 1 illustrates the CWA framework as conceived by Rasmussen et al (1994) and by Vicente (1999). At the centre of the figure at right is a grey area that represents-in the most general way-human activity in some work context. The arrows represent different possible activity sequences. Around the outside of the central area are five factors that interact to shape the activity sequences that are possible and reasonable. Instead of specifying activity sequences, CWA specifies the forces that will discriminate reasonable from unreasonable sequences of activity

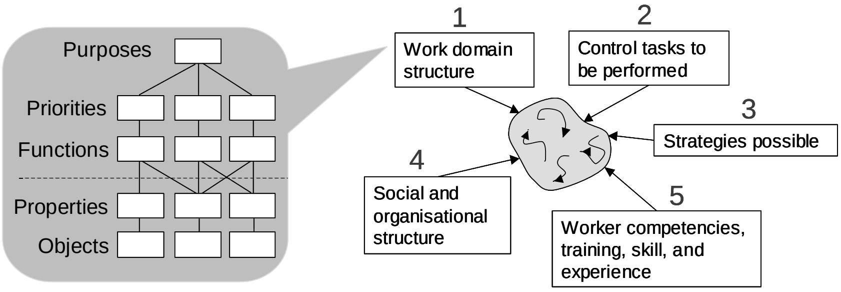


Figure 1 Cognitive Work Analysis framework and structure of Work Domain Analysis

First, the structure of a work domain will partly constrain what is reasonable behaviour. For example, a pilot will not be able to travel from origin A to destination B in a time less than is technically possible given the capability of his aircraft. Similarly, through conventional rules and practices, a pilot will be constrained from flying into controlled airspace without a clearance, even though it might be physically possible. The "physical" limits of the aircraft and the "intentional" limits of aviation practice therefore constrain the pilot's activity. An important part of CWA involves identifying such properties of the work domain itself because they constrain the possibilities for action. This is termed Work Domain Analysis (WDA).

Second, if the system is to achieve its purpose, various control tasks need to be performed. At the coarsest level, control tasks in aviation include familiar operations such as taxi, take off, level out, navigate, communicate, descend, approach, and land. Control tasks are described in general terms, but they will shape the kinds of activities seen. Therefore, navigation is a necessary control task for aviation, regardless of how it is done and by whom, and cockpit activity will reflect that necessity. This is termed Control Task Analysis (CTA).

Third, activity sequences will be constrained and shaped by the strategies a work crew chooses for executing control tasks. As designers, we can shape strategies for carrying out control tasks by varying the kind of human-system interface and the kind of decision support tools we make available. This is termed Strategies Analysis (SA).

Fourth, activity will be constrained and shaped by how control tasks are shared between members of a team (eg captain and first officer) and between humans and flight systems. For example, activity that is possible and reasonable will vary significantly between a manual landing and an automated landing. This is termed Social-Organisational Analysis (SOA).

Fifth, activity will be constrained and shaped by the degree of training and experience that human operators bring to their tasks. This is termed Worker Competencies Analysis (WCA).

These five general classes of constraints form the basis of the CWA approach to analysing human-system interaction. In this paper we are principally concerned with the WDA phase, which is the phase that differs most from other modelling methods. The so-called "abstraction hierarchy" framework that usually underlies WDA is indicated at right in Figure 1 and is the first of the five major columns in Table 1. The abstraction hierarchy is a way of describing the physical and intentional constraints in a domain of work. The bottom two layers (objects and properties in the hierarchy at left of Figure 1) provide information about the physical elements and physical properties that make up a work domain. The top three layers (functions, priorities and purposes) provide information about how the physical properties of a work domain are put to use to serve human purposes.

In the abstraction hierarchy, physical properties are coordinated to support the basic functions or operations of the work domain. To give an aviation example, control surfaces are configured so that, when interacting with the laws of aerodynamics, flight is achieved along a chosen route. Functions are supported in a way that respects the priorities and values of the work domain (flight is constrained to a routing allocated by ATC and aircraft position remains within defined boundaries). When functions are achieved in a way that is consistent with the priorities and values, the overall purpose(s) of the work domain are achieved. Links between nodes provide 'what-why-how' relations. For any given node, nodes linked to it from a lower level indicate 'how' the property, function, priority or purpose of the node is achieved, whereas nodes linked to it from a higher level indicate ‘why’ the object, property, function, or priority is being included in the definition of the work domain.

In the following section there are some examples of CWA in action from some of our recently performed work. Finally we evaluate how useful the CWA approach is.

Examples of CWA in use

We have used CWA at various points across the aviation system life-cycle (Sanderson, Naikar, Lintern, & Goss, 1999). Table 1 shows the phases of CWA in the columns and the steps of the system life-cycle in the rows. Rows 1-5 indicate system design and evaluation steps undertaken before a system is implemented; rows 6-7 the implementation and test steps; rows 8-10 the selection of personnel and development of training systems; rows 11-14 normal use and evaluation; and rows 15-16 the response to changing conditions during the system's lifetime. The arrow at right of Table 1 indicates that analyses performed at one part of the system life cycle (1-16) can usually be reused after minimal adjustment for another part of the life cycle.

In this section we provide three examples of CWA in action: one from knowledge elicitation work with search-and-rescue (SAR) crews, one from work on Australia's proposed Airborne Early Warning and Control (AEW&C) platform (both tender evaluation and team design), and one developed in work on the F/A-18 (Hornet) upgrade. These examples are mapped onto Table 1. Further information about the AEW&C and SAR work can be found in the conference proceedings (Naikar, Drumm, Pearce, & Sanderson, 2000; Elliott, Watson, Crawford, Sanderson, & Naikar, 2000). Yet another instance of CWA in action for design is found in the conference proceedings for patient monitoring in medicine and for approach and landing monitoring and information systems (Watson, Sanderson, & Anderson, 2000).

Table 1 Cognitive Work Analysis phases over the system life-cycle

Phase	Step in System Life-Cycle		Work Domain Analysis	Control Task Analysis	Strategies Analysis	Social-Organisational Analysis	Worker Competencies Analysis
Design	1	Requirements					
	2	Specification					
	3	Design	Proc Cntrl				
	4	Modeling and simulation					
	5	Design evaluation	AEW&C	AEW&C		AEW&C	
Development	6	Implementation					
	7	Test					
Operational preparation	8	Simulator development	F/A-18				
	9	Operator selection					
	10	Operator training	F/A-18				
Use	11	Routine use	SAR	SAR			
	12	Non-routine use					
	13	Maintenance					
	14	Performance evaluation					
Re-evaluation	15	System upgrade					
	16	System retirement					

Knowledge elicitation for SAR using CWA concepts

Analyses that emerge from CWA are based on a variety of sources, including examination of documents (for example, concept of operations, incident reports, manuals, and operating procedures); structured interviews with subject matter experts, participant observation, and so on. An example of how knowledge can be elicited within a CWA framework comes from structured interviews we conducted with Search and Rescue (SAR) pilots (Elliott, Crawford, Watson, Sanderson, & Naikar, 2000). The goal of the interviews was to develop a framework for understanding routine use and for evaluating SAR crew performance.

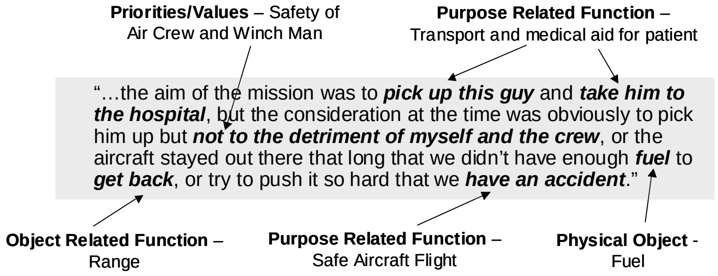
The critical decision methodology (CDM) was adapted for the purpose (Klein, Calderwood, & MacGregor, 1989). Consistent with the CDM, we took a case-based approach in which pilots were asked to recount an incident or episode that was non-routine in some way. However, unlike the CDM which uses probe questions to enable participants to reflect on their thought processes when making important decisions, our adaptation of the CDM methodology probes for information that would help us build CWA-based analyses. For example, at suitable points, the interviewer asked questions that probed each of the five levels of abstraction in the WDA, as follows:

- Functional purpose: ‘If you were to sum up the overall purpose of your role in one sentence, what would that be?’
- Priorities and values: ‘What aspects of your environment are you trying to maximize and minimize? What are your priorities in order to achieve the mission goal?’
- Purpose-related function: ‘What is the goal of doing that?’
- Physical function: ‘What does that piece of equipment actually do? What function does it actually carry out?’
- Physical objects: ‘What physical objects are you exploiting at this stage?’

The probe questions were designed to elicit information about each level of abstraction in the WDA abstraction hierarchy.

After the interview, analysts coded utterances for material relevant to the five levels of abstraction in the WDA. In some cases the evidence was directly in the answers to the probe questions. In other cases the evidence emerged from the SAR pilot’s general narrative. An example of how an utterance from the pilot’s general account was decomposed into evidence at each of these levels is given in Figure 2.

On this basis, Elliott et al (2000) constructed a WDA that distinguished the domain of risk and the domain of resources for mitigating the possible consequences of risk. A representative sample with some simplifications is given in Figure 3. The full analysis consisted of 94 separate nodes, with one functional purpose, six priorities and values, 11 purpose-related functions, 35 object related functions, and 50 physical objects. In Figure 3, some of the nodes are outlined in bold to show the connection of means and ends. For example, the company may be interested in improving their operations. Starting from nodes higher in the abstraction hierarchy, such as ‘minimise time to care needed’ the company can seek the various functions and tools that contribute to that function, and start to speculate on alternative arrangements that might minimise the time to care. In the example in Figure 3, the company might decide to upgrade beacon homers or to explore the market for new equipment to detect and locate emergency beacons.



“…the aim of the mission was to ***pick up this guy*** and ***take him to the hospital***, but the consideration at the time was obviously to pick him up but ***not to the detriment of myself and the crew***, or the aircraft stayed out there that long that we didn’t have enough ***fuel*** to ***get back***, or try to push it so hard that we ***have an accident***.”

Figure 2 Coding of an utterance by SAR pilot using WDA levels of abstraction.

Alternatively, the company many be interested in the possible impact of an upgrade in technology. A change in beacon homer performance characteristics will affect a variety of processes, functions, and priorities at the higher levels. The WDA allows the analyst to trace through the areas possibly affected, and to make a judgment about the effect. When a full CWA has been done, other phases of analysis of CWA, such as an understanding of operator control tasks or strategies, can be enlisted to help with such judgments.

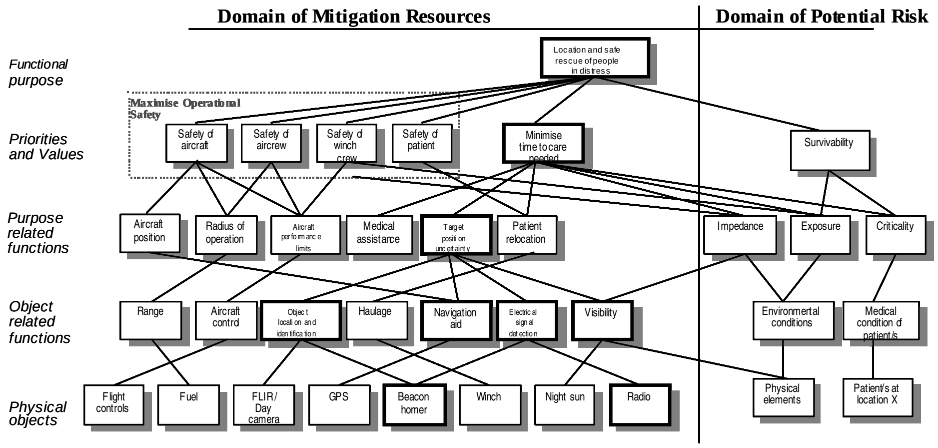


Figure 3 Representative WDA that emerged from the SAR interviews

AEW&C

Starting with methods such as that shown for SAR, we have used CWA—and specifically WDA—at the tender evaluation stage for AEW&C. AEW&C was many years away from existence when CWA modelling started. No truly comparable system existed to the one envisaged. Normally, tender evaluation tends to emphasise physical functionality of a system, which is described at the objects and properties levels of the WDA. This does not provide any evaluation of whether the physical properties of the system will work together effectively to help human operators coordinate the functions of the work domain most effectively, and whether they will do so according to the priorities of the domain so that the overall purpose of the system is reliably achieved.

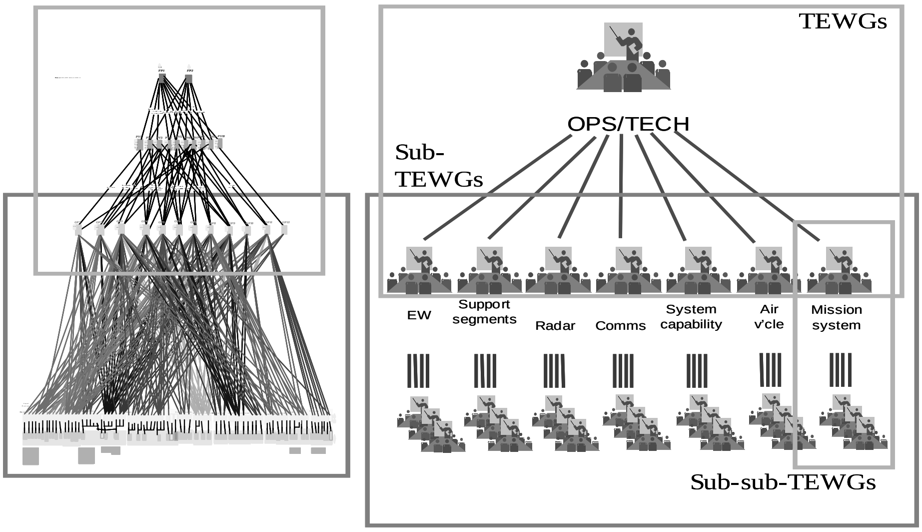


Figure 4 Evaluative framework used for AEW&C tender evaluation: WDA at left. Structure of Tender Evaluation Working Groups (TEWGs) at right.

By evaluating the effectiveness of the proposed designs not only at the lower two physical levels of the abstraction hierarchy, but also at the top three purposive levels, a more comprehensive evaluation against objectives was achieved. As Figure 4 shows, a collection of Tender Evaluation Working Groups (TEWGs) evaluated design proposals for AEW&C using the WDA framework, alongside other methods. Each sub-sub-TEWG evaluated specified technical properties and provided advice to Sub-TEWGs. Each Sub-TEWG evaluated overall performance of a technical system, but also performed the evaluation against multiple functions of AEW&C (see left side of Figure 4) rather than just physical capabilities. An OPS/TECH TEWG then evaluated mission functions against priorities and overall purpose of AEW&C. This allowed a comprehensive and objective comparison of the three proposals to be considered. This procedure was the first time that CWA had been used for tender evaluation and was considered to be valuable (Naikar, & Sanderson, 2001).

More recently, Naikar and colleagues used CWA to evaluate options for crew composition, training, and crew workstation configuration for AEW&C, again in the absence of any existing equivalent of the platform (Naikar, Drumm, Pearce, & Sanderson, 2000; Naikar, Pearce, Drumm, & Sanderson, 2002). A variant of CWA control task analysis (CTA) was used. For each arrangement of crew composition, training and workstation configuration, the CTA outlined which crewmember would be tasked with which work functions at which phase of mission. With this technique, Naikar and colleagues were able to identify the factors that defined the boundaries on practical crewing solutions and proposed a possible crewing solution for AEW&C that had not previously been considered.

F/A-18 and training

In further work, Naikar used the WDA framework to guide the identification of training needs and training system (eg simulator) needs for the F/A-18 (Naikar and Sanderson, 1999, Lintern & Naikar, 2000). In this analysis, which is shown in its most general form in Table 2, each level of the functional structure of the F/A-18 platform was equated with a particular training need and with the functional requirements of a training system (simulator). A full WDA of F/A-18, similar in some respects to that used for AEW&C, guided the details at each level. For example, the identification of priorities and values in the F/A-18 work domain indicated a set of important criteria against which trainee performance could be evaluated and indicated that a training system must be capable of providing situations that would exercise such priorities and collect data relevant to them.

Evaluation of CWA

The previous section outlines three recent applications of CWA to human-system integration issues that have hitherto not explicitly been addressed with CWA. Table 1 shows that they represent only a small fraction of the possible applications of CWA in the analysis, modelling, design, and evaluation of human-machine systems. Further examples can be found in Naikar, et al., (2002).

How much better might CWA be doing than other approaches to such issues? What follows is a series of observations based on seeing many CWA efforts over the last six years or so, many at first hand but many reported by others.

On the positive side, CWA appears to provide a clear framework for analysing the main factors influencing human-system effectiveness (see the five factors in Figure 1). The framework is a helpful guide to where effort should be expended in getting further information and balancing different forms of information. Moreover, CWA analyses developed in one context (row of Table 1) often ‘roll over’ to help solve problems in other contexts. In addition, CWA appears to be helpful in synthesizing the results of analyses performed with other techniques.

Table 2 Framework for inferring training and simulator needs from a WDA.

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 fulfil the functional 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 functions satisfy system 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

CWA can also help different communities communicate. Research and development communities composed of people with different scientific backgrounds often find CWA a useful framework for integrating their concerns because of its ‘systems’ qualities. For aviation psychologists, CWA can provide a framework for putting knowledge of human cognitive and perceptual strengths and limitations into to a rich operational context where team performance and organisational constraints will also matter. For engineers, CWA can provide a simple way to introduce key factors relating to human cognition and decision making that will influence the effectiveness of human-system interaction. For systems developers and software engineers, there is a structural similarity between CWA and existing software engineering techniques, and notions of abstraction on both sides are easy to confuse. However, as Leveson (2000) has noted in her important application of CWA to the US Traffic Collision Avoidance System (TCAS), CWA can provide a framework for capturing the intention behind the design of a proposed system that can guide the technical evolution of the system throughout its lifetime.

On the negative side, CWA has been criticised for the apparent imprecision and time-consuming nature of its methods in the face of possible alternatives (Lind, 1999). There is not space to do much more than point to these issues here and to acknowledge that there are certainly areas where further formal definition and methodological precision would help. Overall, evaluating CWA is complex because CWA has the following properties, any of which could be subject for evaluation:

- It is based in a particular scientific model of human-environment interaction
- It is a philosophy of engineering human-machine systems
- It is an organisational framework for the phases of modelling required
- It includes particular modelling techniques that impose certain syntactic requirements.

More broadly, to evaluate CWA we might borrow some ideas from philosophy of science, adapt them to applied research and development (see Figure 5) and see how CWA fares. Lakatos' (1974) notion of a scientific research program focuses on a series of investigations informed by a particular theoretical orientation, rather than on particular investigations within the program. The program has a *hard core* of theoretical assumptions that cannot be questioned without bringing the whole enterprise into question. Around the hard core is a *protective belt of auxiliary hypotheses* that have emerged from investigations that extend or better define the scope and applicability of the hard core. The *positive heuristic* consists of rough guidelines on profitable investigative paths to pursue to expand the protective belt, indicated in Figure 5 by long arrows pointing rightwards, extending the reach of the theory underlying the program. The *negative heuristic* indicates investigative paths that are unprofitable or premature under the assumptions of the program, because they bring the hard core into question (indicated by short arrows at left).

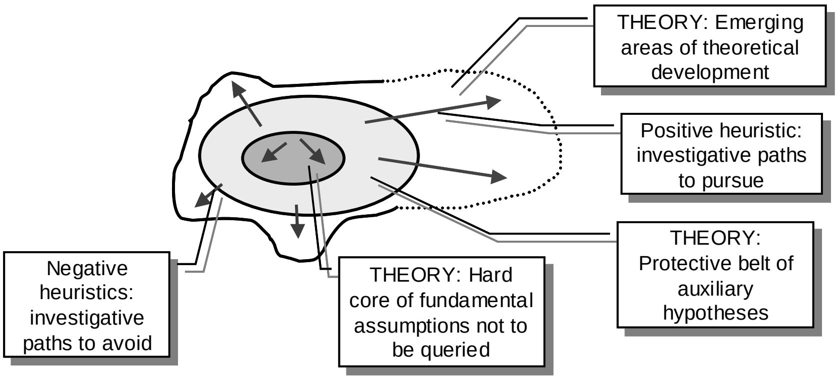


Figure 5 Lakatos' conceptualisation of scientific research programmes

Lakatos' framework may help to describe CWA as an engineering framework, and some of the sociology of the R&D community associated with CWA. The hard core of CWA could be considered CWA's theoretical roots in an ecologically-oriented view of human-environment interaction, and its commitment to 'formative' rather than normative or descriptive modelling. The protective belt could represent current hypotheses about the implications of CWA's theoretical roots and where it can and cannot be applied. The positive heuristic currently points to testing hard core predictions about the organisation of complex human-system interaction, applying CWA in new domains and extending it to new problems in the system life cycle. The negative heuristic may include issues relating to the syntactic structure of WDA models (always five levels?), the handling of control mechanisms (part of the work domain or not?) and questions relating to the primacy of ecological over cognitive considerations.

Lakatos does not give clear guidelines on how a research program is to be evaluated against rivals but its success probably lies in the balance between progressive and degenerative aspects of the program. A progressive program is one in which the theoretical framework gives rise to questions and predictions that have not been prefigured by other theories or frameworks, whereas a degenerative program is one that fails to do so. Chalmers (1982) refers to this balance as the degree of fertility of a research program. It could be argued that the degree of fertility of the ideas underlying CWA is high in terms of its ability to make novel predictions and provide theoretical synthesis on issues relating to psychology and human-environment adaptation (Yu, Lau, Vicente, & Carter, 1998; Vicente & Wang, 1998). Moreover, although no formal comparison of methods has been done, some proponents feel that CWA is particularly helpful compared with other approaches when answers are needed about the human-system engineering of radically new systems very early in their life cycle (see examples herein).

It is probably in relation to the apparent degree of fertility that some of the zeal associated with CWA arises. Reasonably enough, theorists and practitioners may not wish to abandon a program of investigation with a high perceived degree of fertility. They may tolerate some level of incomplete theoretical closure, the challenge of rival approaches, and methodological difficulties, in the interests of reaping the benefits. It is important for theorists and practitioners using CWA continually to assess whether the level of tolerance of these factors is justified. For example, for many people, learning to conduct WDA in particular is difficult. Moreover the reliability of the technique across different analysts is only just starting to be evaluated (Bisantz, Burns, & Roth, 2002). Lind (1999) has recently noted methodological and conceptual problems with using the abstraction hierarchy to perform WDA of physically engineered systems-systems hitherto believed to be the most straightforward to represent. Although the CWA community will question the details of Lind's criticisms and his suggested solutions, the fact that they have been posed is salutary for CWA as a whole.

Conclusions

CWA has proven to be useful in air defence and ATC contexts as well as in many other domains. At present, CWA is practised by a relatively small but growing ‘school’ of cognitive engineers. The future of CWA depends on (1) whether it continues to provide conceptual tools to handle new problems in the design of human-system integration environments, (2) whether it does so sufficiently better than other techniques that the effort of learning it is justified, (3) whether CWA analytic products prove to be useful across the whole system lifecycle, and (4) whether basic CWA methods can be sufficiently well-defined that a wide variety of practitioners can reliability perform them (Sanderson, 2003).

The future of CWA also depends on how easily practitioners can take its basic underlying principles and synthesize analytic products for the purpose at hand, as has recently been done for the aviation domain by Leveson (2000), Naikar et al. (2000), and others. There are many other areas relevant to aviation where CWA can make an analytic contribution, such as defining instrumentation and sensor requirements so that higher-order properties of systems can be displayed (eg mass and energy balances and flows) (Reising & Sanderson 2002a, b). Ultimately, the continuing presence of unique areas of proven usefulness will be the determinant of CWA's success.

Note

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References

Bisantz, A., Burns, C., & Roth, E. (2002). Validating methods in cognitive engineering: A comparison of two work domain models. *Proceedings of the Human Factors and Ergonomics Society 46th Annual Meeting*. (pp. 521-525). Santa Monica, CA: HFES.

Chalmers, A. (1982). *What is this thing called science?* Brisbane: University of Queensland Press.

Elliott, G., Watson, M., Crawford, J., Sanderson, P., & Naikar, N. (2000). Knowledge elicitation techniques for modelling intentional systems. *Proceedings of the Fifth Australian Aviation Psychology Symposium*. Manly, November 20-24.

Klein, G. Calderwood, R., & MacGregor, D. (1989). Critical decision method for eliciting knowledge. *IEEE Transactions on Systems, Man, and Cybernetics,* 19(3), 462-472.

Lakatos, I. (1974). Falsification and the methodology of scientific research programs. In I. Lakatos and A. Musgrave (Eds.), *Criticism and the growth of knowledge.* Cambridge, UK: Cambridge University Press.

Leveson, N. G. (2000). Intent specifications: An approach to building human-centred specifications. *IEEE Trans. on Software Engineering* 26(1), 15-35.

Lind, M. (1999). Making sense of the abstraction hierarchy. *Proceedings of the Cognitive Science Approaches to Process Control conference (CSAPC99).* Villeneuve d'Ascq, France. 21-24 September.

Lintern, G., & Naikar, N. (2002). The use of work domain analysis for the design of training systems. *Proceedings of the 44th Annual Meeting of the Human Factors and Ergonomics Society: Vol 1*. Santa Monica, CA: HFES.

Naikar, N. & Sanderson, P. M. (1999). Work domain analysis for training-system definition and acquisition. *International J. of Aviation Psychology,* 9(3), 271-290.

Naikar, N., & Sanderson, P. (2001). Evaluating system design proposals with work domain analysis. *Human Factors*, 43(4), 529-542.

Naikar, N., Drumm, D., Pearce, B., & Sanderson, P. (2000). Designing new teams with cognitive work analysis. *Proceedings of the Fifth Australian Aviation Psychology Symposium*. Manly, November 20-24.

Naikar, N, Pearce, B., Drumm, D., & Sanderson, P. (2002). A Formative Approach to Designing Teams for First-of-a-Kind, Complex Systems. *Proceedings of the 21st European Annual Conference on Human Decision Making and Control*. 15-16 July, University of Glasgow. pp. 162-168

Naikar, N., Drumm, D., Pearce, B., & Sanderson, P. (in press). Designing teams for first-of-a-kind, complex systems with Cognitive Work Analysis. *Human Factors.*

Naikar, N., Lintern, G., & Sanderson. (2002). Cognitive Work Analysis for air defence applications in Australia. *State of the Art (SOAR) Report on Cognitive Systems Engineering*, Human Systems Information Analysis Center (HSIAC), Wright-Patterson AFB. U.S. Department of Defense. Pp. 162-199.

Rasmussen, J., Pejtersen, A. M., & Goodstein, L. P. (1994). *Cognitive systems engineering*. New York: John Wiley & Sons.

Reising, D. C., & Sanderson, P. (2002a). Work domain analysis and sensors I: Principles and simple example. *International Journal of Human-Computer Studies*. 56(6), 569-596.

Reising, D. C., & Sanderson, P. (2002b). Work domain analysis and sensors II: Pasteurizer II case study. *International Journal of Human-Computer Studies*. 56(6), 597-637.

Sanderson, P. M. (2003). Cognitive Work Analysis. In J. Carroll (Ed.), *HCI Models, Theories, and Frameworks: Toward an Interdisciplinary Science.* New York: Morgan-Kaufman.

Sanderson, P., Naikar, N., Lintern, G., & Goss, S., (1999). Use of Cognitive Work Analysis across the system life cycle: Requirements to decommissioning. *Proceedings of the 43rd Annual Meeting of the Human Factors and Ergonomics Society*. Santa Monica, CA: HFES. Pp 318-322.

Vicente, K, & Wang, J. (1998). An ecological theory of expertise effects in memory recall. *Psychological Review*, 105, 33-57.

Vicente, K. (1999). *Cognitive work analysis: Toward safe, productive, and healthy computer-based work.* Mahweh, NJ: LEA.

Watson, M., Sanderson, P., & Anderson, J. (2000). Designing auditory displays for team environments. *Proceedings of the Fifth Australian Aviation Psychology Symposium*. Manly, November 20-24.

Yu, X., Lau, E., Vicente, K. J., & Carter, M. (1998). Advancing performance measurement in cognitive engineering: The abstraction hierarchy as a framework for dynamical systems analysis. *Proceedings of the Human Factors and Ergonomics Society 42nd Annual Meeting*. (pp. 359-363). Santa Monica, CA: HFES.