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# BOOK REVIEW

***Cognitive Work Analysis: Towards Safe, Productive, and Healthy Computer-Based Work.*** Kim J. Vicente, Mahwah, NJ: Lawrence Erlbaum Associates, Inc., 1999, 392 pages, $89.95, cloth; $45.00, paperback.

Reviewed by Neelam Naikar
*DSTO Australia*

Gavan Lintern
*Aptima Inc.*
*Woburn MA*

Cognitive Work Analysis constitutes a suite of analytic techniques developed in response to the contemporary challenges posed by complex information systems. It was pioneered by Jens Rasmussen (see Rasmussen, Pejtersen, & Goodstein, 1994) in the context of nuclear power control room design and has more recently been extended to a variety of other systems by a small but growing number of human interface scientists. A recent special issue of this journal (Volume 9, Number 3) has outlined the relevance of Cognitive Work Analysis to aviation. In particular, modern aircraft cockpits exemplify the complex information system for which this form of analysis was developed (Lintern, 1999).

Kim Vicente is one of the leading advocates of Cognitive Work Analysis and currently directs what is possibly the most active research program in this area. His new book, *Cognitive Work Analysis*, constitutes a major contribution to this emerging framework. Many will, we imagine, have been as challenged as we have by earlier treatments of this topic. Vicente has brought a new clarity and cohesion to it, not by simplifying it but by unfolding the concepts of Cognitive Work Analysis in a tutorial style that illuminates and complements what has appeared before.

Requests for reprints should be sent to Gavan Lintern, Aptima Inc., 12 Gill Street, Suite 1400, Woburn, MA 01801. E-mail: linternᵃaptima.com

He proceeds systematically through an account that identifies the essential challenges in the design of contemporary work systems and the role that work analysis can play in meeting those challenges. He then contrasts normative, descriptive, and formative approaches to work analysis within the context of complex information systems. He describes the analytic techniques of Cognitive Work Analysis, explaining the nature and goals of each technique and how each contributes to the overall analysis of a representative system. As he proceeds, he clarifies assumptions and distinctions that are crucial to the understanding of Cognitive Work Analysis.

## ISSUES FOR WORK ANALYSIS

There are three thematic concerns that shape the arguments made in this book, all of which are relevant to aviation. One is that the course of events in a complex sociotechnical system cannot be anticipated completely. Workers must therefore be capable of flexible, adaptive behaviour and interfaces must be designed to support that. Another concern is that new technologies offer radically new approaches to work. However, designers fail to take advantage of many new opportunities because they are caught in an evolutionary task-artifact cycle in which existing work practices are allowed to constrain the options for new designs. The final concern is that although the physical and social environment places fundamental constraints on workplace safety and productivity, there is a tendency within many forms of work analysis to focus exclusively on the human cognitive system. Cognitive Work Analysis is offered as a means of resolving these concerns.

### Flexible, Adaptive Action

Cognitive Work Analysis is explicitly tailored to the unique demands of complex sociotechnical systems. These are open systems that are frequently subject to events that cannot be anticipated by workers or system analysts. Such situations do not permit the use of pre-planned work procedures. Rather, workers must respond with adaptive, problem solving behaviour that is tailored to the local context. Indeed, this is the primary value of retaining human workers in complex sociotechnical systems.

Vicente observes that workers have typically played this demanding role in an informal fashion without appropriate support from computer-based information systems. However, given the substantive threat posed to complex sociotechnical systems by unpredictable contingencies, and the importance of adaptation in dealing with these situations, computer-based information systems should be explicitly designed to support workers in that role. A proposal originally forwarded by

Rasmussen and further emphasised by Vicente is that the interface must enable workers to finish the design in a flexible and situated manner.

### Revolutionary Design

A key aim of Cognitive Work Analysis is to support revolutionary rather than evolutionary design. Evolutionary design is based on analyses of current practice and leads to designs that support that practice. When design follows this pattern opportunities for the development of new and more efficient work practices are lost. This is a pattern of design activity that Carroll, Kellogg, and Rosson (1991) identified as the task-artifact cycle. According to Vicente, techniques that appear to bypass the task-artifact cycle, such as rapid prototyping and scenario-based design, do not actually avoid the cycle but iterate through it many times.

Cognitive Work Analysis emphasises the constraints of a work system, such as its functional structure and its control tasks. It is not explicitly constrained by current devices or current work practices and is thus characterised as device and event independent. Specific features of devices and work practice emerge as design solutions late in the analysis and are based on the constraints of the work context.

### An Ecological Perspective

Cognitive Work Analysis is founded on an ecological perspective. By the use of the word *ecological*, Vicente refers to the constraints imposed on action by the physical and social context in which work occurs. Vicente contrasts this perspective to the more popular cognitive approach, which focuses on constraints of the human cognitive system. By reference to a set of case studies, including the Three Mile Island nuclear power plant accident, Vicente shows how a cognitive approach to design can lead to significant problems in the workplace. He argues that, although cognitive constraints are relevant, there is a need to initiate the design process from a consideration of the ecological constraints.

## FORMS OF WORK ANALYSIS

The early chapters of Vicente's book examine various normative and descriptive approaches to work analysis and contrast them to the formative approach. Normative approaches to work analysis identify ideal ways in which work should be performed while descriptive techniques describe how work is actually accomplished. It is the normative and descriptive forms of analysis that have led to the

three themes for the book mentioned earlier, that is, the need to design for adaptive, flexible behavior, the limitations imposed on design by the task-artifact cycle, and the undue emphasis on cognitive constraints.

Vicente offers a formative approach to work analysis that can resolve his three thematic concerns. The formative approach models intrinsic work constraints as a means of identifying the technological and organisational requirements that must be satisfied for effective support of work. *Formative* as used here means to form or fashion from first principles. In Cognitive Work Analysis, formative implies a fashioning on the basis of the characteristics of the problem, such as the functional requirements as identified through the analyses.

## Normative Approaches to Work Analysis

Within his discussion of normative models, Vicente contrasts instruction- and constraint-based analyses. The distinction is that instructions specify what should be done while constraints identify opportunities for action and specify what should not be done. Most normative techniques, such as sequential flow and timeline analysis, identify temporally ordered sequences of actions for completing a task and are therefore instruction-based approaches. The major concern with these analyses is that because they make unrealistic assumptions about human work the procedural specifications that follow from them are often cumbersome or incomplete. Hence the paradoxical work to regulation strike or the ludicrous situation in which workers are accused of malicious rule following. Even worse, workers are ill prepared to cope with unanticipated events and may be led towards procedures that exacerbate an already dangerous situation.

## Descriptive Approaches to Work Analysis

Descriptive work analyses, such as those associated with the paradigms of situated action, naturalistic decision making, activity theory and distributed cognition show the flaws in procedural specifications. They reveal that workers typically behave in flexible and adaptive ways and often converge on patterns of behaviour that are more robust and economical than those specified by normative techniques. Nevertheless, as for normative constraint-based analyses, designs based on descriptive analyses cannot support adaptation to unanticipated or infrequently encountered events and are subject to the problems of the task-artifact cycle. Vicente emphasises that although descriptive analyses offer useful insights, they should not be the only basis on which computer-based information systems are designed.

## A Formative Approach to Work Analysis

Intrinsic work constraints identify boundaries on worker action. They reveal multiple opportunities for action by identifying what should not be done (rather than what is or what should be done) and do so independently of particular devices or work practices. An assumption of Cognitive Work Analysis is that premature commitment to particular forms of devices and to specific forms of activity can unnecessarily constrain design solutions. The arguments developed here are especially relevant to aviation where design has been guided (either formally or informally) by normative or descriptive forms of analysis.

Vicente illustrates the merits of a device- and event-independent constraint-based approach by describing the relative usefulness of directions versus maps for spatial navigation. Instructions can be more efficient because they identify an optimum sequence of actions while maps, in contrast, represent spatial relationships in a form that requires identification of a route. Maps, however, offer more flexibility because they reveal different routes to the same location. This is particularly useful in the face of unanticipated events such as traffic jams. Maps are also more general than directions because they reveal the route from any one point to any other point. Hence, maps support novel travel plans and adaptations to changing circumstances. They also support better recovery from errors.

As should be evident from this analogy, maps are both device and event independent (they do not specify either the means or the actions by which one should move towards a destination). A set of constraints is like a map in the sense that the multiple possibilities for satisfying a goal and limits on action are shown. Where intrinsic work constraints are made evident in an information system, workers have the flexibility to adapt within the remaining space of possibilities. Such an approach allows workers to respond to unanticipated contingencies, and to follow their subjective preferences, while at the same time satisfying the demands of the job by staying within the constraint-based boundaries.

## COGNITIVE WORK ANALYSIS

The five phases of Cognitive Work Analysis focus on the constraints of the work domain, control tasks, potential strategies, forms of social organisation and cooperation, and worker competencies. The gradual transition of analysis through the five phases from the work context to the workers themselves is consistent with the ecological orientation. Vicente addresses the conceptual nature of each phase of analysis and offers a set of modelling tools for each. He also shows how each phase of analysis can contribute to designs that support adaptive, flexible problem solving.

## Work Domain Analysis

Work Domain Analysis focuses on the functional structure of a system and not the actual behaviour of workers acting on the system. The result is a two- or three-dimensional matrix shown as figure 7.12 in Vicente's book. One dimension maps the functional structure of the work domain onto an abstraction or means-end hierarchy over the levels of purposes, values, general functions, physical resources, and physical form. The other dimension displays a decomposition of the structural elements of the work domain at the various part-whole levels of granularity. A third dimension may be added by developing different maps of the abstraction-decomposition structure from the perspectives of different stakeholders.

This abstraction-decomposition matrix is independent of specific devices, events, or workers, and is valid for many different situations including ones that have not been anticipated by workers or by system designers. In much the same way that a map lays out opportunities for travel, the abstraction-decomposition matrix lays out opportunities for functional action. Any reasonably complex system will offer diverse challenges (many unanticipated) and diverse opportunities for action. Flexible, adaptive action will be supported where those opportunities are revealed to workers.

## Control Task Analysis

Control Task Analysis focuses on what needs to be done in known, recurring classes of situations such as start up, normal production, and shut down in process control. In line with a constraint-based approach, Control Task Analysis records what needs to be done in these situations and the possibilities for how it might be done but does not identify precisely how it will be done. It records elements associated with information gathering, with evaluation, and with action in a work domain. Within these broad categories there are states of knowledge (e.g., alerts, system states, goals states) and information processing activities (e.g., detection of change, judgement of significance of information, formulation of action plans).

Traditional information-processing methods assemble elements such as these in a linear sequence. However, those techniques foster characterisations of novice rather than expert behaviour. Descriptive studies have shown that experts rarely follow the steps from perception to decision making and action in a linear sequence. Rather, they seem to develop a set of subroutines that can be linked in different ways to deal with diverse situations.

Vicente suggests that Rasmussen's decision ladder (see figure 8.4 in Vicente's book) can be used as a template for modelling behaviour according to the routines used by experts. The decision ladder accommodates opportunistic action by way of shunts and leaps between various information-processing activities and states

of knowledge. It also accommodates different start points. Control Task Analysis can therefore identify multiple and diverse paths that might be exploited by experts. Hence, rather than forcing workers to engage in all of the activities of a novice we can design systems that deliberately support expert action.

## Strategies Analysis

In Strategies Analysis, the focus is on ways of performing control tasks. Fault diagnosis, for example, might be performed by pattern recognition or by use of a decision table. The first strategy relies heavily on the experience and expertise of the troubleshooter while the second relies on the expertise and knowledge of those who created the table. A *strategy* is a process of knowledge transformation and is defined as a category of cognitive tasks that transforms an initial state of knowledge into a final state of knowledge (p. 9). This definition can be contrasted with the more common usage in which a strategy is a specific and characteristic pattern of activity (e.g., Frederiksen & White, 1989).

Information flow maps can be used for describing strategies. In contrast to descriptions that take the form of a sequence or a pattern of steps, information flow maps offer an idealised process representation from which particular instances of strategy implementations can be generated. As shown in figure 9.7 of Vicente's book, this form of representation depicts a strategy in terms of the relevant cognitive processes and the potential information linkages between processes. A particular strategy might be executed in a number of different ways and may even be adjusted in mid course. Information flow maps permit these variations to be represented as stable constructs irrespective of the particular sequence of cognitive operations employed in any single or idiosyncratic situation.

## Social Organization and Cooperation Analysis

Social Organization and Cooperation Analysis is concerned with the distribution of work demands across human workers and machines, and the supporting mechanisms of communication and cooperation. To readily adapt to changeable circumstances, complex sociotechnical systems require flexible, distributed organisational structures. Vicente uses a study by Rochlin, LaPorte, and Roberts (1987) of operations on the flight deck of an aircraft carrier to illustrate that organizational structures in complex, open systems cannot be completely preplanned in detail. Rather, there is a strong requirement for self-organization through local adaptation to changing circumstances.

Features examined in this analysis are actor competencies, requirements for access to information or means for action, needs for communication to facilitate

coordination of distributed activities, workload sharing requirements, safety and reliability issues, and compliance with regulations. The abstraction-decomposition space, decision ladders, and information flow maps can be used to allocate boundaries of responsibility across actors or groups of actors. For instance, the different steps in a strategy could be split up between human workers and machines. The descriptions that emerge from the Social Organisation and Cooperation Analysis reveal the information and communication requirements for each role within the organization. Thus, human-system interface supports for work activities can be explicitly tailored to meet the responsibilities of individual actors or work teams.

### Worker Competencies Analysis

The final phase of Cognitive Work Analysis focuses on the competencies that workers need if they are to function effectively in their particular role. Hence, it is only at this stage that the particular constraints of human workers become the focus of the analysis. Decisions made in earlier phases of Cognitive Work Analysis will have implications for the essential competencies because responsibilities of workers will be affected by whether or not particular work demands are allocated to machine automation or to human operators.

The skills, rules, and knowledge taxonomy provides a structure for matching work demands to our knowledge of human capabilities and limitations. Each level in the taxonomy defines a category of cognitive control or a way in which the constraints in the environment are represented and processed internally by workers. In brief, knowledge-based behavior involves analytical reasoning, rule-based behavior involves an if-then mapping between a familiar perceptual cue and an appropriate action, and skill-based behavior involves real-time, direct coupling to the environment. Because there is interaction in complex sociotechnical systems among the three levels of cognitive control, designers of interfaces must provide support for all levels. Moreover, interfaces must not force cognitive control to levels higher than that demanded by the task.

## CONCLUDING COMMENTS

Cognitive Work Analysis is based on a strong conceptual foundation that has matured since its beginnings in Rasmussen's work in the 1970s. Vicente emphasises this conceptual basis and argues that it will become increasingly important with the continuing evolution of work, particularly in the areas of computer-supported work, automation, and complex information systems, all of which are

important to modern aviation. Cognitive Work Analysis is, however, a developing system. Vicente offers a perspective that incorporates the latest ideas but there are noticeable differences in terminology, representational tools, and organization to those offered by Rasmussen et al. (1994). Nevertheless, his treatment remains true to the foundational assumptions of the earlier formulations. The differences might be viewed as inevitable in a field that is making a serious attempt to cope with the emerging challenges posed by our new style of computer-based information systems.

The substantive point of contact between Cognitive Work Analysis and other forms of Cognitive Task Analysis is the shared emphasis on cognitive elements, (see for example, Seamster, Redding, & Kaempf, 1997). However, the field of Cognitive Task Analysis is populated with a diverse and fragmented set of methods that partially overlap and that have no explicit linkages to each other. Cognitive Work Analysis brings a degree of order to this endeavour by offering a systematic and well-integrated suite of analyses that covers the requirements. In particular, the emphasis on the work domain appears to be unique to Cognitive Work Analysis. This is the most difficult part of the overall analysis and possibly the most important for aviation, especially for system definition. It is essential to the design of support for unanticipated events as encapsulated in the philosophy of formative design.

In our view, Cognitive Work Analysis offers a major contribution to the development of modern aviation systems by bringing a coherent perspective to the problem of automation. In some discussions, automation is seen as problematic and those promoting it are placed on the defensive. At other times it is said that the human operator is properly relegated to the role of systems monitor. Within the theoretical perspective of Cognitive Work Analysis neither of these views is appropriate; neither machine nor human is relegated to a subsidiary role. The analysis allocates essential roles to each and promotes a synergistic relationship in which system functionality achieved by the two working together in their proper roles exceeds that possible where one dominates at the expense of the other. The manner in which functions are properly allocated across human and machine is one of the strong elements of Vicente's book.

More generally, this book makes a comprehensive contribution to the challenges facing design within complex large-scale projects, such as those within the aviation domain, that are and have been causing problems. Vicente offers a strong conceptual perspective for guiding the design of such systems, and also provides the essential tools for the design process. Cognitive Work Analysis is a framework that will find increasing use especially for the design of systems that incorporate new functionalities. It is of particular value for its application to full-scale integration of distributed elements and its emphasis on flexibility and adaptation in operation. These are elements that are becoming increasingly important in our modern computer-based aviation systems.

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