AN EXAMINATION OF THE KEY CONCEPTS OF THE FIVE PHASES OF COGNITIVE WORK ANALYSIS WITH EXAMPLES FROM A FAMILIAR SYSTEM

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Cognitive work analysis (CWA) is recognized, principally, for work domain analysis. Relatively little research has been directed at the remaining four phases of CWA and, as a result, the concepts of these phases of analysis are less well understood. This paper examines the concepts of all five phases of CWA with examples from a single 'system' – a home. A home is a highly familiar system that is characterized primarily by social or intentional constraints. The examples in this paper, therefore, complement the case study provided by Vicente (1999) of DURESS, a thermo-hydraulic microworld simulation that is defined largely by physical or causal constraints. In addition, this paper provides a starting point for examining several issues relating to the later phases of CWA, including whether or not they are useful or unique, their relationship to other approaches for work analysis, and methodological shortcomings.

INTRODUCTION

Cognitive work analysis (CWA) is gaining attention as a promising framework for work analysis. Much of the research in this area, however, has focused on work domain analysis, the first phase of CWA. Relatively little attention has been paid to the remaining phases of CWA, namely, control task analysis, strategies analysis, social organization and cooperation analysis, and worker competencies analysis. As a result, the concepts of these phases of analysis are less well understood.

The aim of the work reported in this paper was to examine the key concepts of the five phases of CWA with examples from a single 'system' – a home. This system was chosen, firstly, because it is a highly familiar system. Hence, the task of investigating the concepts of CWA would not be hampered by a lack of knowledge of the system. Secondly, this system was chosen because it would complement the case study provided by Vicente (1999) of DURESS, a thermo-hydraulic microworld simulation. Whereas DURESS is a causal system that is primarily constrained by physical laws, or the laws of nature, a home is an intentional system that is primarily constrained by social laws, conventions, and values.

This paper does not address all of the concepts of the five phases of CWA nor does it provide a complete CWA of a home. Instead, the paper focuses on concepts that have direct implications for analysis and design, and it presents examples from a home that facilitate the examination of these concepts. Given the large body of work that is available on work domain analysis, the paper gives emphasis to the remaining phases of CWA. Finally, the paper highlights a number of conceptual and methodological issues relating to the later phases of CWA.

OVERVIEW OF COGNITIVE WORK ANALYSIS

CWA is a formative approach to work analysis that focuses on how work <u>can be</u> done (Rasmussen, Pejtersen & Goodstein, 1994; Vicente, 1999). This framework recognizes that workers have many options with respect to what to do, when, and how. Therefore, rather than focusing on how work <u>should be</u> done (normative approaches) or how work <u>is</u> done (descriptive approaches), CWA focuses on the constraints that shape work in the first place. These constraints can accommodate a variety of work patterns, including novel behaviors to deal with unanticipated events. As there are several types of constraints that can shape workers' behavior, several dimensions of analysis are necessary.

WORK DOMAIN ANALYSIS (WDA)

WDA focuses on the purposive and physical environments in which workers operate. The purposive environment includes the reasons for which a system exists whereas the physical environment includes the resources that are available. The purposive and physical environments define the fundamental problem space of workers by specifying the objectives to achieve with the resources that are available.

The main modeling tool for WDA is the abstraction-decomposition space (ADS). Figure 1 shows a sample of an ADS of a home (Naikar, Hopcroft & Moylan, 2005). The vertical axis of the ADS represents the purposive and physical problem space of the home in terms of several concepts or levels of abstraction. The horizontal axis represents the purposive and physical problem space of the home at different levels of detail or decomposition. The relationships between the levels of abstraction are means-ends relations whereas the relationships between the levels of decomposition are part-whole relations. As the ADS is event-independent, the representation in Figure 1 is relevant to many different situations. By basing designs on the ADS, WDA aims to support workers in dealing with a variety of situations, including novel or unanticipated events.

CONTROL TASK ANALYSIS (ConTA)

ConTA focuses on <u>what</u> needs to be done in a work domain. It complements WDA by identifying the activity that is necessary to achieve the objectives of a system with a given

	Whole House	Rooms and Subspaces (e.g., Kitchen)	Contents and Components (e.g., Dishwasher)
Functional Purposes	E.g., Shelter, Well-being, Residential laws and regulations, Environmental protection.	E.g., Provision of meals and beverages, Financial Savings, Time savings, Environmental protection, Safety, Health, Enjoyment.	E.g., Cleaning, Financial savings, Time savings, Environmental protection, Safety, Health.
Values and Priority Measures	E.g., Total income greater than total expenses, Chore time less than *n* hours, Maximize leisure time, Minimize use of natural resources (e.g., water, power), Maximize privacy, Maximize hygiene, Maximize pleasure.	E.g., Expenses less than *n* dollars, Chore time less than *n* hours, Minimize use of natural resources (e.g., water, power), Minimize risk of injury, Maximize hygiene, Maximize nutrition, Maximize pleasure.	E.g., Minimize expenses, Minimize chore time, Minimize use of natural resources (e.g., water, power), Minimize risk of injury, Maximize hygiene.
Purpose-related Functions	E.g., Meals and beverages, Rest, Recreation, Personal care and grooming, Housework, Maintenance, Administration etc.	E.g., Storage, Preparation, Cooking, Serving, Cleaning.	E.g., Washing, Rinsing, Drying.
Object-related Processes	Functional capabilities and limitations relating to co-location of: storage, preparation, cooking, serving, cleaning, laundering, sleeping, entertaining etc.	Functional capabilities and limitations relating to: cooling, freezing, cutting, stirring, heating, washing, rinsing, drying, wiping, disposing etc.	Functional capabilities and limitations relating to: support of objects, flow of water, storage & release of chemicals, temperature selection etc.
Physical Objects	Inventory, material characteristics, and topography of whole house including co-location of rooms.	Inventory, material characteristics, and topography of kitchen including: fridge/freezer, cutlery, utensils, stove, oven, microwave, crockery, pots and pans etc.	Inventory, material characteristics, and topography of dishwasher including: shelves, pipes, detergent dispenser, temperature selection dial etc.

Figure 1. A sample of an ADS of the home.

set of physical resources. The aim of ConTA is to support workers in dealing with known, recurring classes of situations.

ConTA has three key concepts. First, ConTA recognizes that in many systems, the same goals may be accomplished in different ways depending on the situation. Hence, an input-output analysis that identifies what needs to be done, without specifying exactly how it should be done or by whom it should be done, is appropriate for analyzing activity in these systems.

Second, ConTA recognizes that in many systems, activity can be characterized as a set of work situations and/or work functions (Naikar, Moylan & Pearce, 2006; Rasmussen et al., 1994). The classification of activity into work situations is appropriate if work is organized around time or location. The classification of activity into work functions is appropriate if work is organized in terms of its content. In some systems, activity is best characterized as a combination of work situations and work functions. These are systems in which activity within a work situation, or set of work situations, is further organized around the functions to perform.

Figure 2 is a contextual activity diagram that illustrates some of the combinations of work situations and work functions that are likely to occur in the home. The work situations are defined by stages of the day and week (horizontal axis) and the rooms of the home (diamonds). The work functions are shown in the circles. The boxes around the circles on the right side of the diagram indicate that work functions are likely to occur at more stages of the day on weekends compared with weekdays. The diagram also shows that work functions are likely to occur in more locations of the home on weekends compared with weekdays.

Third, ConTA recognizes that activity can be further characterized in terms of the decision-making functions or control tasks that are required for each work situation and/or work function. The decision ladder, which provides a template for representing control tasks, departs from traditional models of information processing because it: need not be followed in a linear sequence but allows shortcuts from one part of the template to another; accommodates various start and end points; and allows activity to flow from right to left rather than only from left to right. Hence, the decision ladder can be strung together in different ways to represent the opportunistic form of cognitive activity that characterizes expert behavior in complex environments.

Figure 3 shows a decision ladder for the work function *prepare meals/beverages*. The decision ladder depicts some of the: events that may act as alerts in preparing meals/beverages (e.g., time); information that may be necessary (e.g., what ingredients are required); assessments of the current situation (e.g., am I in a position to prepare these meals/beverages); options that are available (e.g., modifying recipes); goals that may be considered in selecting an option (e.g., prepare nutritious meals/beverages while minimizing expenses); target states that are desirable (e.g., which meals/beverages to prepare); tasks and resources that are required to achieve the target state (e.g., obtaining ingredients by driving to the supermarket requires car, fuel, money, driving, buying ingredients etc); and procedures that might be followed (e.g., refuel the car before heading to the supermarket).

STRATEGIES ANALYSIS (SA)

SA focuses on identifying the different ways in which activity can be accomplished. Therefore, whereas ConTA is concerned with what activity is needed, SA is concerned with how the activity can be done. While information flow maps may be used for modeling strategies, this tool has not yet been developed in a generic format but has only been created for specific applications.

SA has four key concepts. First, SA is not concerned with defining detailed sequences of actions or mental processes. Instead, SA is concerned with identifying general ‘categories of cognitive procedures', which are idealized, abstract descriptions of particular sequences of operations.

Second, SA recognizes that several strategies are usually possible for performing a single activity. A number of strategies are possible for preparing a meal in the home. To illustrate, it is possible to: follow a written recipe to prepare a meal; prepare a familiar meal from memory; create a meal on the basis of one's knowledge of the functional properties of ingredients (e.g., taste, aroma, texture, cooking times, nature of interactions with other ingredients, reactions to different cooking processes); create a meal by trial and error (i.e., try out various combinations of ingredients and cooking styles and check the results by sight, taste, aroma, consistency etc); and prepare a meal by heating up a pre-cooked or frozen dish.

Third, SA recognizes that workers will often switch between multiple strategies while performing a single activity in order to deal with task demands. The strategies that are selected at any given point in time will depend on the performance criteria of each strategy, such as, the amount of time, memory load, and level of knowledge that is required for each strategy. Preparing a meal by heating up a pre-cooked dish requires less time than creating a meal on the basis of one's knowledge of the functional properties of ingredients. Therefore, the former strategy is more likely to be selected when there is limited time for preparing a meal. Workers' subjective task formulation, or how workers conceive of a task, may also affect which strategy is chosen. A person who formulates the act of preparing a meal as a chore that must be performed to satisfy hunger is likely to adopt a different strategy to a person who formulates the act of preparing a meal as a creative process that is challenging and rewarding.

Finally, SA recognizes that it is important to identify the range of strategies that are possible as opposed to the range of strategies that are used by workers. Workers may not use certain strategies because they are resource intensive but, as a result, they might not be using the most effective strategies. By designing effective support for these strategies, workers will be able to adopt strategies that they otherwise might not use.

SOCIAL ORGANIZATION AND COOPERATION ANALYSIS (SOCA)

SOCA focuses on who can carry out the work requirements of a system, how it can be distributed or shared, and how it can be coordinated. Whereas Rasmussen et al. (1994) and Vicente (1999) describe SOCA predominantly as a way for analyzing existing organizational structures, this section presents SOCA in a way that is relevant for designing new organizational structures.

SOCA has four key concepts. First, SOCA recognizes that in many systems, flexible organizational structures that can be adapted to local contingencies are essential for dealing with unanticipated events. SOCA, therefore, does not attempt to define a single or best organizational structure. Instead, SOCA is concerned with identifying the criteria that may shape or govern how work might be allocated across actors.

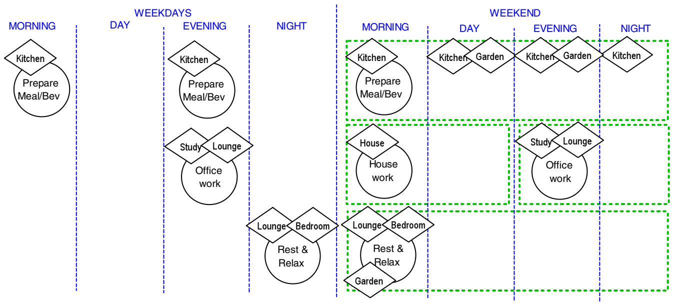

Figure 2. A contextual activity diagram for the home.

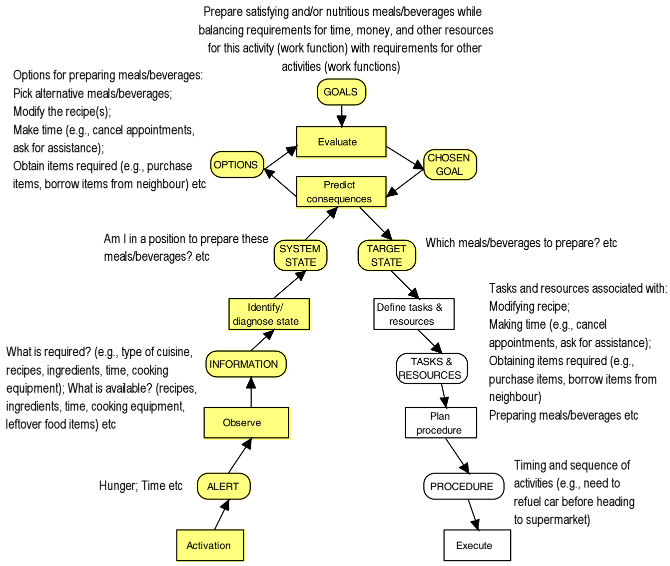

Figure 3. A decision ladder for *prepare meals/beverages*.

Rasmussen et al. (1994) and Vicente (1999) discuss six criteria that may shape how work is allocated in a system, which are illustrated here in the context of the home: (1) Actor competency – the competencies of actors may shape how the responsibilities for preparing meals versus gardening are allocated in the home; (2) Access to information or means for action – the access that actors have to information (e.g., what ingredients are required for a meal) or the access that actors have to the means for action (e.g., car) may shape who drives to the supermarket to do the grocery shopping; (3) Coordination – the requirement to minimize communication may shape the allocation of housework to a single actor in the home; (4) Workload – the requirement for workload sharing may shape the allocation of housework to multiple actors in the home; (5) Safety and reliability – the requirements for safety and reliability may shape what responsibilities are allocated to children in the home; (6) Compliance – the requirement for compliance with established practices or regulations may shape the hiring of technical experts to carry out electrical repairs in the home. Some additional criteria that may influence how work is allocated in the home include: (7) Enjoyment – an actor who enjoys gardening may assume this responsibility; and (8) Availability – an actor who notices that the plants need watering may assume this responsibility.

Second, SOCA involves examining how the work demands of a system may be allocated and distributed across actors as a result of applying various criteria or sets of criteria. The allocation and distribution of work may be defined in relation to the work domain, work situations, work functions, control tasks, and strategies. Hence, the modeling tools from the earlier phases of CWA are also relevant here.

Figure 3 illustrates how the decision ladder can be used to examine the allocation and distribution of actors across control tasks. Given particular criteria, the shaded areas of the decision ladder might be allocated to Actor A and the remaining areas might be allocated to Actor B. The decision ladder highlights the information, coordination, and resource requirements of the actors. Actor A must have access to information about what ingredients are required for meals/beverages and how much time is required for preparation. Furthermore, Actor A must communicate this information to Actor B. Then, to prepare meals/beverages, Actor B must have access to resources like ingredients and cooking equipment. The other modeling tools of CWA may be used in a similar fashion to identify actors' information, coordination, and resource requirements.

Third, as well as examining how work may be allocated and distributed in a system, SOCA is concerned with the form of communication, or social organization, that may be adopted for coordination in a system. Different forms of social organization are possible, such as, autocratic, authoritarian, and hierarchical (Rasmussen et al., 1994; Vicente, 1999). In a home, the forms of social organization that are adopted may depend on the particular individuals in the home as well as on the nature of the work allocation and distribution. Furthermore, the social organization of a home may be adapted to local contingencies. A home with a democratic organization might adopt an autocratic form in the event of an emergency.

Finally, SOCA recognizes that organizational structures in many systems are generated on line and in real time by multiple, cooperating actors responding to the local context. SOCA is, therefore, not concerned with planning upfront the nature of the organizational structures that should be adopted in different situations. Instead, by identifying the set of possibilities for work allocation, distribution, and social organization, SOCA aims to support flexibility and adaptation in organizations by developing designs that are explicitly tailored to the requirements of the various possibilities.

WORKER COMPETENCIES ANALYSIS (WCA)

WCA focuses on the competencies that workers need to deal effectively with the work requirements of a system. WCA has five key concepts. First, WCA recognizes that the work requirements from the previous phases of CWA shape the competencies that workers require.

Second, WCA distinguishes between three levels of cognitive control that workers can adopt for guiding or performing action in a work domain. Skill-based behavior is defined by highly automated and integrated patterns of action that are performed in real time and that are directly coupled to the environment in a continuous perception-action loop. Chopping up vegetables with a knife, for example, involves skill-based behavior. Rule-based behavior is defined by if-then mappings between familiar perceptual cues in the environment and appropriate actions. Following directions in a recipe to switch the stove to a low heat setting when the contents of a pot start to boil involves rule-based behavior. Knowledge-based behavior is defined by serial, analytical reasoning based on a symbolic mental representation of the relevant constraints in the environment. Substituting an ingredient in a recipe with another ingredient on the basis of knowledge of the functional properties of ingredients involves knowledge-based behavior. These three levels of cognitive control constitute the skills, rules, and knowledge taxonomy.

Third, WCA recognizes that the level of cognitive control that is activated in performing a task depends on how information in the environment is interpreted by workers. Information can be interpreted in terms of signals, signs, and warnings. Signals, which are continuous and quantitative perceptual indicators of time-space patterns, trigger skill-based behavior. For instance, when pouring milk into a measuring jug, the decreasing distance between the level of liquid in the jug and the one-cup marker on the jug is a time-space signal that indicates when to stop pouring. Signs, which are arbitrary but familiar perceptual cues in the environment, trigger rule-based behavior. A tone produced by an electronic scale when a pre-programmed weight is reached acts as a sign to stop pouring milk. Symbols, which are meaningful formal structures that represent the functional properties of the environment, trigger knowledge-based behavior. For example, knowledge of a conversion formula that allows one to calculate how many cups of milk there are in a l-liter carton of milk may be stored as symbols in a mental model.

Fourth, WCA recognizes that whether information is interpreted as signals, signs, or warnings and, consequently, the level of cognitive control that is activated in performing a task, can be influenced by the form in which information is presented to workers. However, other variables like the level of expertise of workers, the degree to which workers reflect on their performance, and the task demands can also influence how information is interpreted by workers.

Finally, WCA recognizes that people tend to execute lower levels of cognitive control more quickly, effectively, and effortlessly than higher levels of cognitive control. Interfaces should, therefore, present information to workers in a way that allows them to rely on lower levels of cognitive control. Nevertheless, higher levels of cognitive control may still be required because the level of cognitive control that is triggered is not just based on the form in which information is presented but also on a number of other variables. Hence, interfaces need to support all three levels of cognitive control.

DISCUSSION

The preceding examination of the concepts of the five phases of CWA raises a number of questions. One question is: are the later phases of CWA useful? This question may be answered in terms of whether or not the later phases of CWA lead to useful designs. Without evaluating designs that are informed by the later phases of CWA, it is difficult to answer this question with certainty. Nevertheless, it is possible to provide some examples of design insights from the CWA of the home that is presented in this paper. First, the abstraction-decomposition space and the decision ladder for the home indicate that decisions about which meals/beverages to prepare are made on the basis of a number of factors, such as, preparation time, nutritional value, cost, and pleasure. These decisions could be supported by an 'electronic cookbook' that allows users to search for recipes for meals/beverages in terms of these criteria. Second, the SA reveals that as well as following recipes to prepare meals, people can create meals on the basis of their knowledge or through trial and error. Hence, an electronic cookbook could offer users the functionality of adding new recipes to its database. Third, the WCA shows that people may need to reason about which ingredients might act as substitutes for other ingredients in a recipe on the basis of their knowledge of the functional properties of ingredients. An electronic cookbook could support this activity at a lower level of cognitive control by presenting users with information about which ingredients can act as substitutes for others.

Another way of evaluating the usefulness of the later phases of CWA is in terms of whether or not they offer a unique perspective for analyzing work compared with other approaches to work analysis. Without a detailed comparison of CWA and other techniques, it is difficult to answer this question comprehensively. However, it is challenging to think of any other single approach to work analysis that generates an integrated, multi-faceted description of a system that leads to all of the categories of design insights that are possible from the five phases of CWA. Moreover, even at the level of single phases, CWA seems to offer a unique perspective. For example, apart from SOCA, there appears to be no other technique that advocates analyzing criteria for work allocation and distribution as a basis for designing flexible organizational structures that can be tailored to local contingencies.

Another question that might be posed is whether or not other techniques can be used for some of the phases of CWA. For instance, can decision-action diagrams (Kirwan & Ainsworth, 1992) be used instead of the decision ladder. A critical difference between decision-action diagrams and the decision ladder is that the former identifies sequences of decisions and actions whereas the latter recognizes that for many systems, the total set of decision and action sequences is too large to specify. The decision ladder is misleading because the connections between the nodes imply a fixed sequence of operation. As discussed earlier, however, the decision ladder allows: shortcuts from one part of the template to another; various start and end points; and flows from right to left rather than just from left to right. Moreover, with respect to the home, the decision ladder was simply used to identify categories of alerts, information, situation assessments, options, goals, tasks, and procedures. Therefore, in this case, the categories or nodes on the decision ladder may be visualized as a set of bubbles. Connections would only be identified between bubbles to record either sequences that are observed or sequences that are constraints (i.e., sequences that must occur).

This discussion should not be taken to imply that other techniques can never be used for some of the phases of CWA. Naikar et al. (2006), for instance, used an adaptation of the critical decision method to construct decision ladders for a military system. It is important to ensure, though, that alternative techniques are consistent with the theoretical underpinnings of CWA, not for the sake of academic rigor, but because CWA offers a particular perspective for analysis and design. If decision-action diagrams were used for SOCA, to determine how work might be allocated or distributed in a system, the end result might be an organizational design that is optimized for a few operational sequences.

Finally, the examination of the concepts of the five phases of CWA raises methodological issues. With respect to SA, for example, it is not clear how to identify the range of strategies that are possible as opposed to those that are currently being used by workers. This problem is exacerbated when the system of interest is a future, first-of-a-kind system and not an existing system. Like the other issues that have been raised in this paper, this is an area for further research.

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