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# Model-Based Approaches for Analyzing Cognitive Work: A Comparison of Abstraction Hierarchy, Multilevel Flow Modeling, and Decision Ladder Modeling

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## ABSTRACT

Model-based approaches to cognitive task analysis rely on abstracting from the problem domain, rather than a description of task performance. Various classes of work analysis models can be distinguished: task models, work domain structure models, and work domain goal models. In this article, we discuss 3 specific model-based approaches: the Abstraction Hierarchy (AH), Multilevel Flow Modeling (MFM), and the Decision Ladder (DL). The AH creates a model of the work domain structure, MFM of work domain goals, and DL of actor tasks. The 3 approaches are compared in the context of a common example—that of a power plant boiler—to show clearly the differences among the 3 classes of techniques.

## 1. INTRODUCTION

An increasing amount of attention is being devoted to techniques for analyzing cognitive work (e.g., Beyer & Holtzblatt, 1998; Rasmussen, Pejtersen, & Goodstein, 1994; Schraagen, Chipman, & Shalin, 2000; Zsambok & Klein, 1997). One way to divide up this literature is to distinguish between techniques for *data collection* and techniques for *modeling* data once it has been collected (Vicente, 1999). More attention has been devoted to data-collection techniques, such as knowledge elicitation methods (Cooke, 1994), than to modeling techniques. Yet, when a great deal of disparate data have been collected (e.g., behavioral measures, communication measures, eye movements, field observations, interview data, physiological measures, survey data, verbal protocols), it is frequently difficult to derive design implica-

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tions directly. The distance to be crossed from description to intervention is overwhelming. Modeling can serve the important role of abstracting from a wealth of data to generate crisp insights that can lead to the identification of useful design interventions.

At the same time, direct comparisons of different work modeling techniques are quite rare. Each technique is frequently only used by the handful of people who were involved in its creation and development (Schraagen et al., 2000). As a result, there is very little understanding of the comparative advantages and disadvantages of different approaches to work modeling. It would be useful to compare alternative techniques, preferably on the same sample problem, so that differences can be clearly identified.

In this article, we examine the differences among three alternative approaches to work modeling: Multilevel Flow Modeling (MFM; Lind, 1981, 1994), the Abstraction Hierarchy (AH; Rasmussen, 1985), and the Decision Ladder (DL; Rasmussen, 1976). Each of these techniques is well known and widely cited in the cognitive engineering community, but the differences among them are not well understood. As far as we know, this is the first time that these three approaches have been compared for the same problem. The comparison focuses on the information requirements derived by each technique.

The remainder of this article is organized as follows. We begin by discussing the nature of model-based approaches for studying cognitive work. We then give details on the three approaches that we have chosen to compare: MFM, the AH, and the DL. Then we compare all three models for the same problem (i.e., a power plant boiler). We discuss the fact that the AH and DL are techniques within a set of analytical frameworks called Cognitive Work Analysis (CWA; Rasmussen et al., 1994; Vicente, 1999).

## 2. WHAT ARE MODEL-BASED APPROACHES?

Model-based approaches are a distinct class of work analysis techniques. Whereas observational approaches provide detailed descriptions of unique instances of people working with technology (e.g., Suchman, 1996), model-based approaches try to abstract from idiosyncratic details to provide a more concise description that has implications for design. MFM, the AH, and the DL are all examples of model-based approaches to work analysis.

Such approaches can be further distinguished by the object of modeling (Vicente, 1999). *Task models* describe the actions that can or should be performed by one or more actors (human or otherwise) to achieve a particular goal. *Work domain structure models* describe the structure of the system being controlled, independent of any particular worker, automation, event, task, goal, or interface. *Work domain goal models* describe desired (i.e., target) states of the system being controlled, independent of any particular worker, automation, task, or interface.

An analogy can be used to illustrate these distinctions. Whereas a person might nail roofing to a beam—an action—the fact that the beam supports the roofing and keeps it from falling down is related to work domain structure. So in that way, a model of how someone could build a house would be a task model. A model of what is needed to have what we consider to be a house—some sort of foundation, support structure, and top covering or roofing—would be a structural work domain model. A model of work domain goals would tell you that the house should have an internal temperature of 20 °C. It does not describe the work domain structure, or outline the actions to get there, but describes the state that the house should be in. These three models would immediately tell you different things—the task model might tell you the steps and order in which you need to do things, the structural work domain model would tell you what weight and type of roof you could support, or how strong your beams need to be, and the work domain goal model would tell you the acceptable states that must be achieved for the house to provide comfortable habitation. Obviously, all three kinds of information are needed to build a house, to make sure that what you have built doesn't fall down and to ensure that it functions correctly!

All three types of models describe how certain intentions can be achieved, though these intentions are quite different. The person who is building the house is working toward a *goal*, or a state to be achieved at a particular time. Goals are relatively dynamic and tend to change; in our example, once the house is built, the actor moves on and works toward another goal. In contrast, the house itself continues to stand and achieve its purpose of providing shelter from the environment. A *purpose*—the overarching intention that a work domain was designed to achieve—is more permanent than a goal. Once the actor, or builder, has moved on to other goals, the house still stands and serves its purpose.

Finally, we need to define the relations within the models. Within a task model, where actions are working toward goals, this connection between an action and its goal can be called an *action means–end relation* (Vicente, 1999). Within the work domain structure model, where objects are connected to the purpose of the work domain, we have a *structural means–end relation* (Vicente, 1999). With the work domain goal model, where work domain target states are connected to work domain functions, we have a *goal–achievement relation* (Lind, 1999b). The nailing done by the house builder is an action means–end relation. That the roofing provides shelter is a structural means–end relation. Using the cooling system to maintain a desired temperature is a goal–achievement relation. Given these definitions, we can proceed to discuss the three modeling approaches.

## 3. A COMMON FOUNDATION

MFM and the AH both developed out of a need for approaches to understand how people operate complex systems (Rasmussen & Lind, 1981). Complex systems are systems with many interacting components that must be controlled to achieve the purpose of the system. With complex systems, one has to consider that unanticipated events may occur and the operators themselves may not be able to describe how the system works completely. To handle this class of work problems, Rasmussen (1985) proposed the AH. The AH developed out of observations of electronic troubleshooters, and, rather than looking at the actions of these troubleshooters, it looked at how they understood the electronics problem itself. MFM was developed in close connection with the AH (Rasmussen & Lind, 1981), first as a grammar for expressing the AH (Lind, 1981) and more recently (Lind, 1999a) as an alternative approach to the AH. Both approaches create a model, but we argue that MFM creates a *work domain goal model* whereas the AH creates a *work domain structure model*. The DL (Rasmussen, 1976) can be viewed retrospectively as a way of supplementing the AH, by mapping action means–end relations into a task model. The AH and DL are the first two analyses in a set of analyses referred to as CWA (Rasmussen et al., 1994; Vicente, 1999).

## 4. THE EXAMPLE

To examine the differences among the approaches, we took the example of a power plant boiler. Because a boiler is often part of a larger system, there are limitations to our models because they only model a subsystem. However, we chose this example because the MFM model is available in the literature (Larsen, 1993) and because it presents a problem on a challenging, but not overwhelming, scale so that we can demonstrate the differences among the approaches. We modeled the following components of the boiler system: the boiler, the heat exchanger, the combustion chamber, the economizer, air and fuel intake valves, and associated piping. These components are not detailed further. (See Figure 1 for a model of the boiler.)

## 5. MFM MODEL

An MFM model is a model of goals and flow structures. Recently, there have been developments in MFM methodology to connect it to the component level (Lind, 1999b). Be-

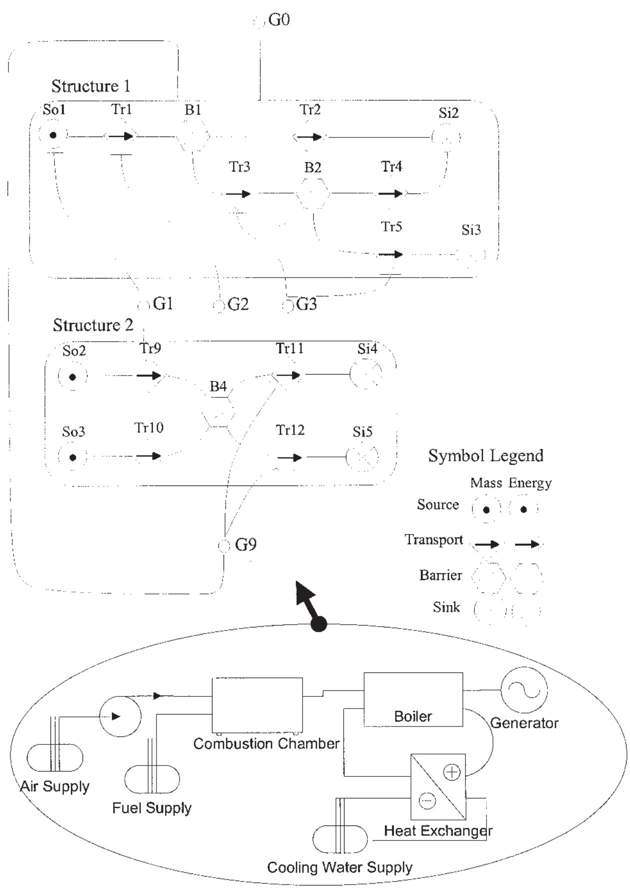


**FIGURE 1** MFM model of the boiler.

cause these connections are not yet detailed, our description focuses on the goal and flow structures of the MFM models. MFM describes the flow of mass and energy through the use of functional primitives. Functional primitives describe work domain components in terms of their most basic action possibilities (e.g., acting as a transport or acting as a barrier). Functional primitives exist as both mass and energy. Beyond mapping out these mass and energy flow structures, MFM models connect these structures to goals, that is, desired states that need to be achieved for the work domain to continue operating. In this way, an MFM model is a work domain goal model, indicating states to be achieved and the work domain structures to use to achieve these states. The connections between the two comprise goal–achievement relations.

In describing the MFM model, we use the following model and its description paraphrased from Larsen, 1993:

> The main goal of the power plant boiler is to provide an energy flow on the generator shaft. This goal is named G0 in the model and the means to achieve it are the flow functions represented by structure 1. … Structure 2 supports three goals named G1, G2, and G3. They are all related with providing and transporting the energy at the first stages of structure1. G1 is the goal of providing a proper ratio between the air and fuel flows. G2 is the goal of having a flame and G3 expresses that a flow of combustion gases is needed to carry the heat into the economiser. … Related to G2 is G9, which is the goal of having a chemical reaction between the fuel and the oxygen. This goal is achieved by structure1. (pp. 28–30)

The first thing to notice is that the model describes five different goals: having a flow of energy, achieving a correct air/fuel ratio, having a flame, having a flow of combustion gases, and having a chemical reaction between fuel and oxygen. These goals describe the states that are needed to operate the boiler under normal circumstances. Note, however, that the goals are *event dependent* (Vicente, 1999) because they change over time. If the boiler is being shut down, for instance, then having a chemical reaction would no longer be a desirable goal. The event-dependent nature of MFM contrasts with the event-independent nature of the AH (see the following section).

The MFM flow structures indicate the functions for achieving the goals; therefore, the connections between the flow structures and the goals are goal–achievement relations. Within the structures, the functional primitives are connected by causal links, which indicate the flow or progression of mass and energy.

Also interesting is the overall structure of the model. The top level is a goal level, followed by an energy structure, followed by a goal level, followed by a mass structure with a goal level that connects back to the first energy structure. Components and their topology are loosely mapped in a structural means–end relation. Whereas the top level goal is the overall state to be achieved, the lower level goals are subgoals that must be achieved to reach the overall state. In general, though, the goal achievement connections can be portrayed in both directions: The functional structures can be used to achieve goals, and the goals can influence the functional structures. The model is not hierarchic, and in fact loops back on itself through G9, reflecting the circular connections between the goals that must be achieved for the boiler to operate under normal conditions. The analyst could presumably continue to develop more and more complex MFM models by dividing the goal description further.

## 6. AH MODEL

The AH model takes a fairly different form. As originally proposed by Rasmussen (1985), it is a hierarchic model of five levels. The top level describes the purpose of the work domain, or what it was designed to do, and the lower levels describe how the objects in the work domain achieve that purpose. In this sense, it is a model of how and why the house is what it is, so the AH is a work domain structure model. Goals to be achieved or actions to be taken are not included. The objects within the work domain are connected to levels that describe why they exist; therefore, the model uses structural means–end relations between the levels.

Describing the model in Figure 2, the top level describes the overarching purpose of the boiler. It is a description of why the boiler was designed (to convert water to steam), to do this safely and maximize earnings. AH models are often most useful to the analyst when there are at least two purposes described, particularly if these purposes create different bounds on how the work domain can be used. The second level is a description of basic principles behind the boiler, in this case, the very basic conversions of mass and energy. The third level describes the processes that occur within the boiler. The last two levels are descriptions of the physical instantiation of the boiler components, with Physical Function describing the capabilities of objects within the work domain and Physical Form describing the condition, location, and appearance of those objects. Between each level, structural means–end relations are indicated, mapping objects to the overall purpose. Within each level, the causal connections between the objects are shown.

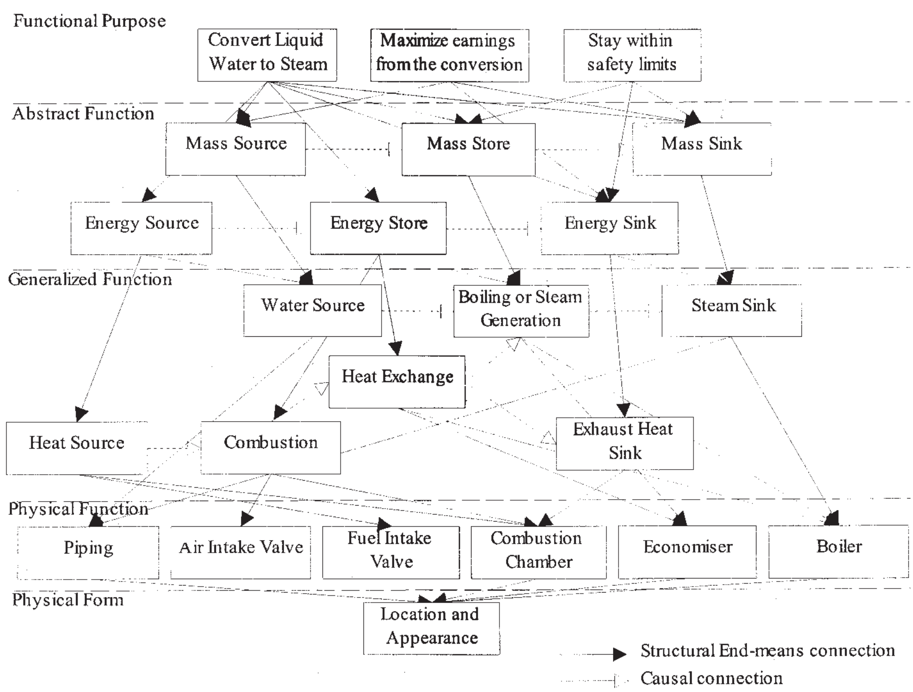


**FIGURE 2** AH model of the boiler.

In comparison with the MFM model, this model describes purpose rather than goals. Because it begins from a description of purpose, and purpose is overarching, there are no "subpurposes." Each level of the model is a different kind of description, and the model is clearly hierarchic. There are no loops between the levels. The structural means–end relation is directional with ends ordered above means throughout the model. As the model moves from top to bottom, it moves from an abstract description to a physical description. Although the model could be reworked at different levels of granularity within each level, the model has a definitive end at the Physical Form layer.

In comparing the MFM model to the AH model, it is seen that the MFM model is a work domain goal model, whereas the AH is a work domain structure model. To the analyst using these approaches, this makes a difference in the kind of information obtained from the analysis. The MFM model reveals states important to predefined modes of operation but does not reveal the overall purpose of the work domain. The MFM model indicates the roles that certain pieces of equipment play in achieving those operational states, which could help an operator to use the equipment or to develop a procedure for using the equipment. In an unanticipated situation, however, the model may not be useful because the goals that have been modeled may no longer be appropriate. This brittleness results from the fact that MFM goals are event-dependent.

The AH model does not make these kinds of assumptions but only reveals how different pieces of equipment contribute to the purpose of the system. In other words, the AH is an event-independent model (Vicente, 1999). Action possibilities are indicated through the understanding of how equipment works, but particular courses of action, target goals, or uses of equipment are not defined. These are unused degrees of freedom at this stage in the analysis and would seem more appropriate as a first analysis of a complex system where operators may have to deal with unanticipated situations.

## 7. DL MODEL

The AH model is limited to describing work domain structure relations because it is a subset of a larger set of analysis called CWA. CWA deliberately distinguishes between work domain structure and task models and recommends that they be performed in separate and distinct modeling exercises (Rasmussen et al., 1994; Vicente, 1999). Whereas CWA recommends an AH model as a first-stage analysis, it recommends a DL analysis (a task model) as the second stage of analysis. So to complete the comparison with the MFM model, we have also created an example of a DL for the problem of the boiler (Figure 3).

A DL provides a template of possible cognitive activities, cognitive states, and actions. The left side of the ladder is largely information-processing activities and states, whereas the right side of the ladder represents decision-making states and actions. The ladder is reproduced entirely for all activities; then the analyst highlights the states and actions that are relevant to the current task. One advantage to the ladder format is that it allows for the easy indication of shortcuts between different actions and states.

From the boiler problem, we took one of the states indicated by the MFM model, that of achieving a correct fuel-to-air ratio, and created a hypothetical DL for that particular task. To reach the proper target output from the boiler, a human or machine actor would have to achieve a certain fuel-to-air ratio. This would likely involve consulting or developing a procedure that would outline a series of actions to be taken. The actor would observe the results of those actions and then readjust targets and settings if needed.

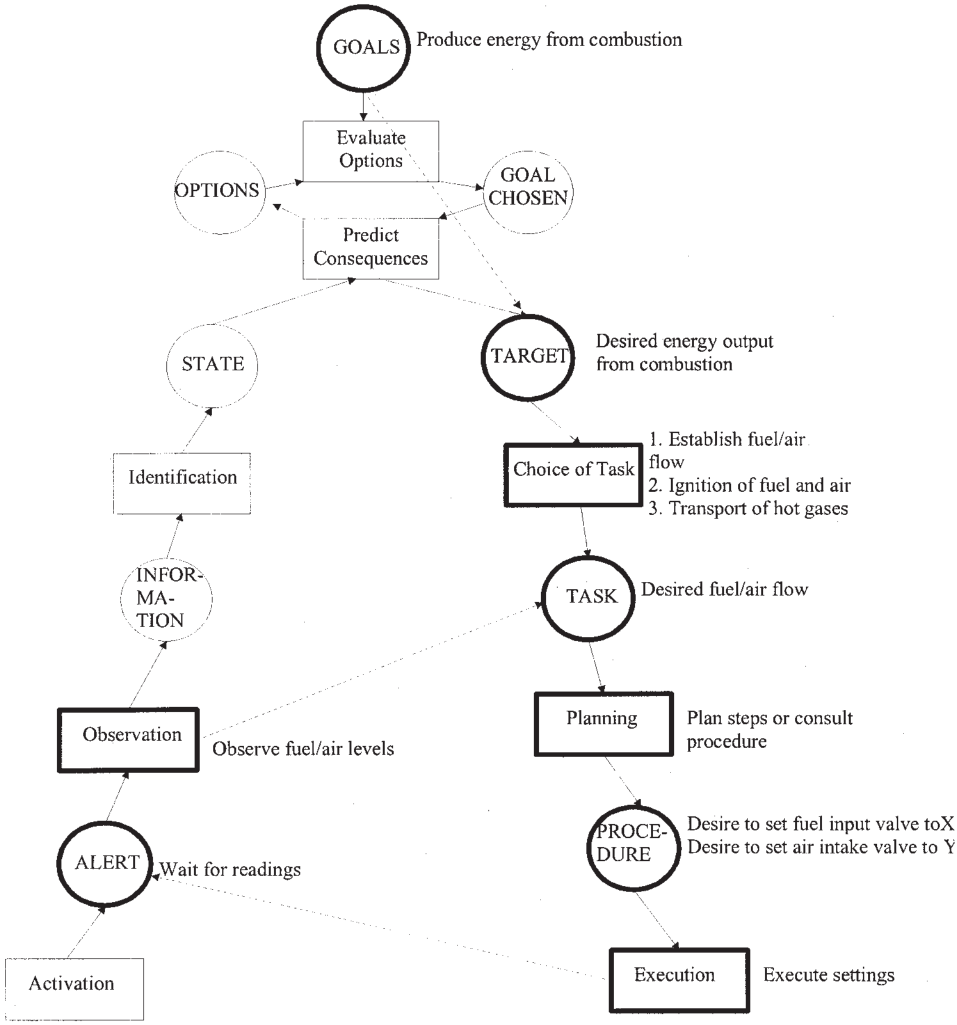


**FIGURE 3** DL for the boiler.

If we compare this model with the MFM model, we see the similarities and differences between the two types of models. Both are driven by an operational state to be achieved, that being energy flow. To get to this state, there are certain tasks to be completed. The DL model describes these as the tasks of establishing fuel-to-air ratio, igniting the mixture, and transporting hot gases. In the MFM model, these three tasks are described as goals G1, G2, and G3. Then in this particular DL, the fuel-to-air ratio task is connected by action means–end relations at the procedure and execution stages. However, in the MFM model, the goals are connected by goal–achievement relations to the mass and energy structures. In terms of describing action and cognitive states, the DL provides a richer description. Actions are detailed down to an executable step. Further, more than just action is described; the DL outlines information-processing stages and highlights cognitive shortcuts. Many of the elements commonly found in a cognitive task analysis are incorporated in the DL, with the advantage that the consistent structure ensures that steps are not missed and shortcutting behavior can be identified. Unlike the AH, we also see that the DL has loops and cycles and is not as formally hierarchic.

## 8. CONCLUSION

This article had several objectives. First, we wanted to demonstrate the usefulness of comparing different approaches to work analysis using the same problem. With this kind of side-by-side comparison, it is easier to see the difference in the outputs of the techniques and hopefully aids practitioners in deciding on the right technique for their situation. More comparisons of this type are needed for other work analysis techniques.

Second, we wanted to illustrate that there are different kinds of model-based approaches that yield different information for the analyst. Within the range of model-based approaches, we wanted to show the difference between a model of a task (the DL model), a model of work domain goals (the MFM model), and a model of work domain structure (the AH model). Within the models, the modeling elements are quite different. The work domain structure model begins with overall purposes, whereas the task and work domain goal models examine the achievement of goals. The AH models work-domain structure at several different levels, whereas the DL model examines action and the MFM model examines goal achievement. Task models show how actions achieve goals, work domain goal models show how functional structures achieve goals, and work domain structure models show how physical components interact to achieve design purposes. We have summarized the comparison in Table 1.

We concede that the example we used in this article is limited because it is a generic problem, and more detailed comparison could be made by showing the techniques on an actual industry problem. The example is illustrative, though, and helps to show the differences

TABLE 1
Comparison of Models

| *Attribute* | *MFM Model* | *AH Model* | *Decision Ladder Model* |
|---|---|---|---|
| Type of model | Work domain goal model | Work domain structure model | Task model |
| Type of structure | Network or cycle | Hierarchy | Cycle |
| Model start | G0 | Functional purpose | Undefined |
| Model end | Undefined | Physical form | Undefined |
| Goals or purposes | Operational goals | Functional purposes | Operational goals |
| Types of relations | Causal goal achievement | Causal structural means–end | Cognitive steps action means–end |
| Information type | Operating goals and mass and energy structures | No operational information, mass and energy structure, clear process and physical information | Operating goals; information-processing steps and stages; Action description; Operational shortcuts |

*Note*. AH = abstraction hierarchy; MFM = multilevel flow model.

among three interesting and potentially useful techniques for work analysis. We feel that all the techniques are better understood through demonstration using a common problem, and we hope that other cognitive engineering researchers will follow this path in comparing these and other techniques.

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