

Cognitive Systems Engineering

New Wine on New Bottles

E. Hollnagel and D.D. Woods

RISØ-M-2330

COGNITIVE SYSTEMS ENGINEERING

New Wine in New Bottles

E. Hollnagel (Risø National Laboratory)

D. D. Woods (Westinghouse Research and Development)

Abstract. This paper presents a new approach to the description and analysis of complex man-machine systems, called Cognitive Systems Engineering. In contradistinction to the traditional approaches to the study of man-machine systems (MMSs) which mainly operate on the physical and physiological level, CSE operates on the level of cognitive functions. Instead of viewing an MMS as decomposable by mechanistic principles, CSE introduces the concept of a cognitive system: an adaptive system which functions using knowledge about itself and the environment in the planning and modification of actions. Operators are generally acknowledged to use a model of the system (machine) they are working with. But similarly the machine has an image of the operator, whether implicit or explicit. The designer of an MMS must recognize this, and

February 1982

Risø National Laboratory, DK 4000 Roskilde, Denmark

strive to obtain a match between the machine's image and user characteristics on a cognitive level, rather than just on a physical level. The paper gives a presentation of what cognitive systems are, and of how CSE can contribute to the design of an MMS, from the cognitive task analysis to the final evaluation.

UDC 65.015.11:159.95

ISBN 87-550-0821-6

ISSN 0418-6435

Risø repro 1982

CONTENTS

	Page
INTRODUCTION	5
WHY IS A NEW AREA OF MAN-MACHINE STUDIES NECESSARY?	5
COGNITIVE SYSTEMS ENGINEERING	9
The Limitations of the Logic of Design	9
The Whole and the Parts of an MMS	12
WHAT IS A COGNITIVE SYSTEM?	16
LEVELS OF DESCRIPTIONS IN MMSs	20
HOW ARE COGNITIVE SYSTEMS ENGINEERED?	21
Cognitive Task Analysis	22
Man-Machine Principles	26
Evaluating the Suggested Design	28
FUTURE TASKS FOR COGNITIVE SYSTEMS ENGINEERING	29
NOTES TO THE TEXT	32
REFERENCE NOTES	34
REFERENCES	35

INTRODUCTION

This paper describes a new approach to thinking about and designing Man-Machine Systems (MMSs). Technological developments, especially the breadth and depth of computer applications, have significantly increased the complexity of MMSs. Present knowledge of MMSs is insufficient to deal with the consequences of today's technological changes - to say nothing of what may lie ahead. This is because existing techniques only address MMSs at a physical or mechanical level (Note 1). The design of a properly functioning MMS requires a different kind of knowledge which describes the cognitive or mental functions of the MMS (Note 2).

WHY IS A NEW AREA OF MAN-MACHINE STUDIES NECESSARY?

The growth of computer applications has radically changed the nature of the man-machine interface. First, through increased automation, the nature of the human's task has shifted from an emphasis on perceptual-motor skills to an emphasis on cognitive activities (e.g., problem solving and decision making). In process control applications today, for example, the human element tends to focus on monitoring and supervisory behavior rather than the detailed control mechanics. Second, through the increasing sophistication of computer applications, the man-machine interface is gradually becoming the interaction of two cognitive systems.

Ever since the introduction of machines into the production process, there has been a need to design a proper interface between man and machine. Because the early machines were an extension of man's physical functions, the MMSs were designed so that the machines could best compensate for the physical

deficiencies of man. The goal was to maximize the total output of the MMS, and little or no consideration was given to the function of the MMS apart from this. The latest evolution of microelectronics created machines which extended the mental capabilities of man. This removed the operator further from the production process, so that instead of controlling a machine he now had to control a process - or to monitor a self-controlling process. Instead of interacting with a physical machine, he now had to interact with a cybernetic machine. The machine is no longer restricted to simple reactions to whatever the operator does, and to simple indications of its own condition. It is instead able to make use of information processing, hence perform very complex activities and communicate in a seemingly intelligent way (Note 3). To meet the challenges of this development requires knowledge not only about the physical functions of man, but also about his mental functions. In other words, the psychology of cognition must be applied to the description and design of MMSs.

Traditional approaches (Human Factors, Engineering Psychology, Ergonomics) to the design of MMSs are unable to address the cognitive interface problems. First, engineering psychology focuses on the limits of human performance in the physical domain (Figure 1), not on cognitive functions: for instance, can an operator reach a control (anthropometric limits), or see a display or read a label (sensory limits). As a result, engineering psychology techniques and guidelines are designed to identify and correct violations of the operator's physical limits. For example, activity and link analyses are designed to determine how much physical activity is demanded of the operator or if related controls and displays are physically associated. Human engineering guidebooks (see Mallory et al. (Note 2) and MIL-STD-1472C) provide criteria for when the human's performance envelope is violated and tips on how to avoid these limits. While this is a necessary (and often under-emphasized) step in interface design, it does not and cannot address the problem of making man and machine work as an effective cognitive system.

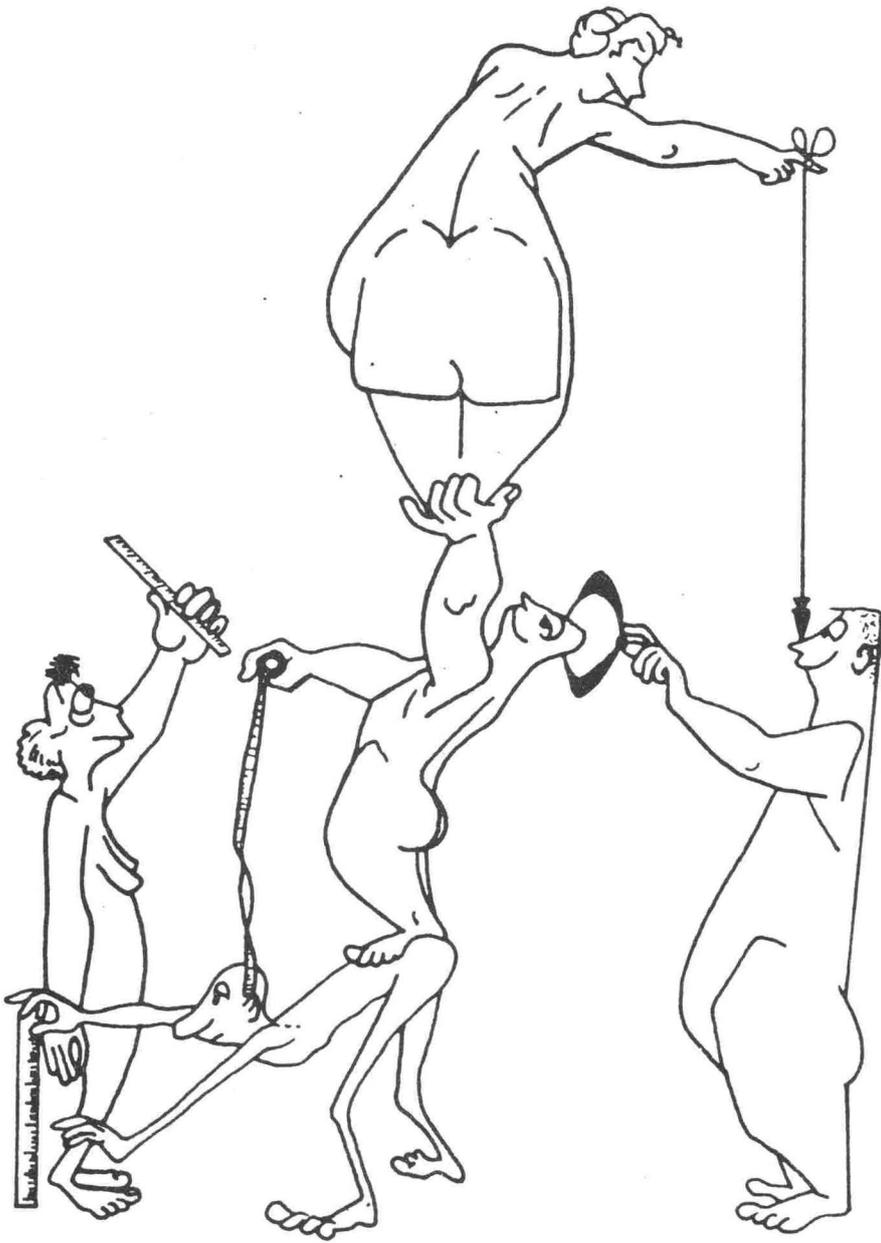


Figure 1. Measuring human performance characteristics in the physical domain.

Second, traditional engineering psychology does not possess the tools, concepts and models, necessary to analyze and understand MMSs from a cognitive viewpoint. To be fair this is partly due to the dominance during the 1930s and 1940s of behaviorism which reduced the human to a black box and instead focussed on what could be observed as stimuli and responses. The typical meta-model underlying engineering psychology sees human information processing as a linear series of fixed processing stages. However, the experience from real-life studies (e.g. Rasmussen & Jensen, 1974) corroborated by advances in cognitive psychology and in the design of "intelligent" computer systems have demonstrated that this approach is inadequate both theoretically and in real-world applications. (Allport, 1980; Hollnagel (Note 3); Kolers, 1979; Neisser, 1976; Norman & Bobrow, 1976 all give criticisms of the linear stage meta-model of information processing, which is caricatured in Figure 2). A new view is emerging which describes human cognitive functioning as a recursive set of operations including both bottom-up or data-driven analysis, that is, analyses arising from information which comes to the operator from the environment, and top-down or conceptually-driven analysis, that is, analyses which starts from information which the operator already has. (See Kubovy & Pomerantz, 1981; Norman & Bobrow, 1976; Palmer, 1975.) This approach to human cognition brings several important features to the design of man-machine systems including an emphasis on conceptually-driven behavior and on methods of studying an individual's performance rather than the performance of a statistical composite (Rasmussen, 1976; Rasmussen & Lind, 1981).

Technological developments alone have changed the nature of the man-machine interface from emphasizing man's physical tasks to emphasizing his cognitive tasks, and thereby made a purely technological approach to MMSs obsolete. The costs and consequences of ignoring the cognitive functions of MMSs are noted in technology failures daily (we need only mention the Three Mile Island accident). As a result a new approach is necessary which will apply and further develop the techniques and knowledge base of cognitive psychology to the design of MMSs.

This area of man-machine studies we call Cognitive Systems Engineering. Our reasons for choosing the term cognitive systems engineering will be clear from the following parts of the paper. Related efforts to deal with some of the same basic problems have been described by names as Knowledge Engineering (Feigenbaum, 1978), Cognitive Reliability (Halpin et al., 1973), Cognitive Factors (Reisner, 1981), Cognitive Engineering (Norman, Note 4), Cognitive Ergonomics (Sime & Fitter, 1978), and others.

COGNITIVE SYSTEMS ENGINEERING

As the subtitle indicates, cognitive systems engineering (CSE) is more than a reformulation of old ideas. The changes in the technological environment have created a demand for thinking about the man-machine relationship in a fresh way. A new interdisciplinary synthesis is required to meet this challenge.

The central tenet of CSE is that an MMS needs to be conceived, designed, analyzed and evaluated in terms of a cognitive system. Like the Gestalt principle in psychology, an MMS is not merely the sum of its parts, human and machine. The configuration or organization of man and machine components is a critical determinate of the outcome or output of the system as a whole.

The Limitations of the Logic of Design

A machine designer works from a model that describes a portion of the physical world. However, the same designer will attempt to build a man-machine interface without a proper model that describes the relevant portion of the psychological world. One mission for CSE is to provide the designer with a realistic

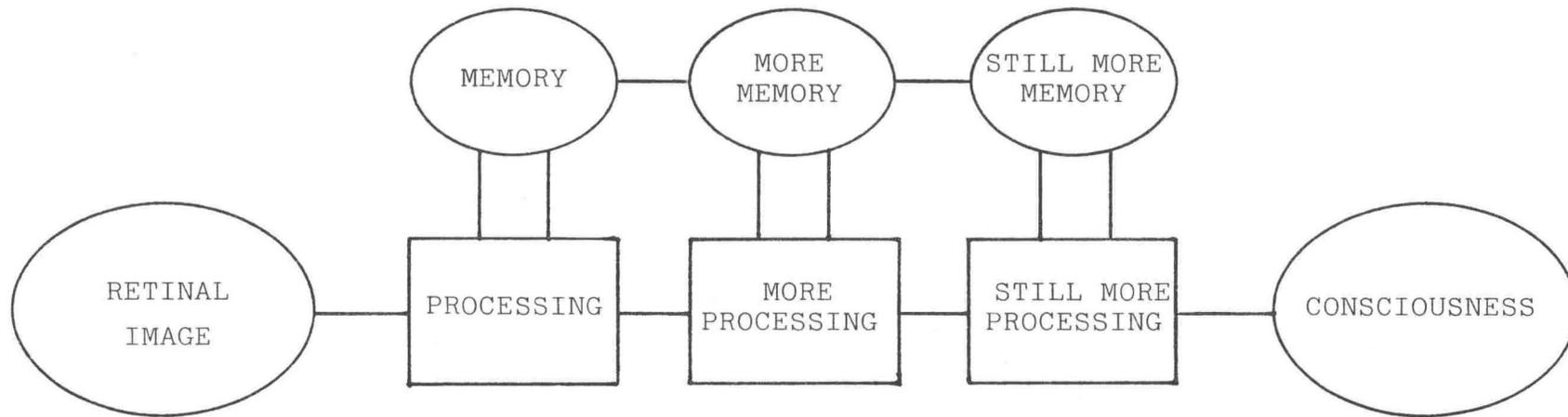


Figure 2. Caricature of the traditional linear stage model of human information processing (adapted from Neisser, 1976).

model of how the human functions cognitively. It is essential to acknowledge that the models that describe the physical and the psychological worlds are not the same. Rules of logic describe the behaviour of the physical world, but human behavior is not necessarily based on an analogous rational mechanism although thinking according to the rules of logic is regarded as the ideal. The failure to recognize this characterizes practically every attempt to make a formal description of a part of human activity. One notable example of that is decision theory, where the normative decision theory has produced an explicit description of the rational decision maker - the so-called homo economicus (cf. Edwards, 1954 & 1961). However, it is also realized that the human decision maker fails to comply with the idealized rational decision maker (e.g. March & Simon, 1958), and several attempts at providing a more realistic decision theory have been made (e.g. Janis & Mann, 1977). It is simply that man functions according to a psycho-logic rather than to a logic. This means that the way in which humans go about making decisions, solving problems, thinking logically, making diagnoses, etc. can be described by rules and principles developed by psychology, rather than by the rules of logic, (e.g. Rasmussen & Jensen, 1974). It is a basic truth that man does not think as a calculus ratiocinator would - which is one reason why philosophers and logicians have strived to construct one for ages. And the designer of an MMS must acknowledge that. The image of the operator should not be of a calculus ratiocinator, but rather of a person - a whole person and not just an information processor. A similar argument can be made with regard to perception, where the pitfall is that the description is given in terms of physics rather than psycho-physics (e.g. Kubovy & Pomerantz, 1981; Runeson, 1977).

It is quite ironic that engineering psychology has accepted that the perceptual capacity of the operator is limited and that there are many cases where it is deficient, when at the same time very little consideration is given to how the operator deals with the information once he has gotten hold of it. The designer apparently assumes that the interface to the

operator is frail, but that otherwise the operator functions as a perfect logical information processing system. CSE is an attempt to change that view, and to provide the designer with a realistic prototypical image of how the operator functions cognitively.

The Whole and the Parts of an MMS

We all know that we may describe a system as a whole or as a collection of parts, and generally agree with the maxim that the whole is more than the sum of the parts. Yet as soon as we turn from the world of words to the world of things, we act as if the whole was nothing more than the sum of the parts. That, at least, seems to be the principle embraced by the majority of analyses and designs which are made of complex systems. In the case of training, for instance, the complete performance is often divided into smaller parts, segments or basic functions. The training is then carried out with respect to the basic functions and to certain combinations of them, with little thought of giving the trainee the overall view. The integration of the performance into a whole is left to the operator. This is an attitude which reflects the ideas of Scientific Management (Taylor, 1911) as well as the physicalistic approach inherent in the empiristic tradition. Training is, of course, not the only example of it. It is rather characteristic of the general attitude to design of MMSs.

One reason for this may be that in designing a machine, it is justifiable to assume that the whole is the sum of the parts. But when dealing with a system which includes human beings, or generally dealing with the so-called exceedingly complex systems (Beer, 1964) where the deterministic analysis cannot be carried out, this assumption is no longer valid.

It is, of course, quite reasonable to consider the separate functions of an MMS in detail. However, one should never forget that they occur against a background of the total functioning

of the system. And when the various functions or tasks have to be distributed among the machine and the operator, it is insufficient to make an a priori assignment. Particularly so when the criterion appears to be that the machine must compensate for the deficiencies of man, i.e. a simple extension of the principle behind traditional human engineering. Take, for instance, an MMS where 95% of the functions can be automated. It is obvious that the system as a whole will function differently when the distribution of tasks between the machine and the operator is 95%/5% and e.g. 80%/20% - the latter alternative not necessarily being less efficient than the former. Boredom and stress, for instance, are aspects of the operator's function which are influenced by the distribution of tasks in the system. And the optimal distribution may easily vary from situation to situation. Consequently, the design of the system should permit a certain latitude in the distribution of tasks (e.g. Rouse, 1977; Vaughan & Mavor, 1972), as it well may if the MMS is conceived of as a cognitive system. The virtue of CSE is that the MMS is thought of as adaptive, and that the goal is to improve the function of the system as a whole, rather than to replace as many as possible of the operator's functions. The operator may eventually be found to be bad at any kind of work which can be described algorithmically. But that does not mean that a simple substitution of him with a machine will improve the function of the total system.

The question of man-machine allocation is an important example of the traditional view of MMSs as merely a collection of independent parts. The task universe is seen as a closed space where sub-tasks are identified and then allocated to man or machine until the space is filled (see Kisner et al., (Note 5) for an example). This approach assumes that overall system performance is a linear function of performance on each sub-task. However, changing task allocation qualitatively changes the nature of the man-machine interface because it transforms the underlying cognitive system, and therefore necessarily affects overall system performance.

First, an operator's ability to detect failures in a dynamic system is a nonlinear function of the architecture of man and machine tasks, e.g., whether the operator is an active element in the control loop or functions as a monitor or supervisor of system operation (Ephrath & Young, 1981). The operator detects failures better when he participates in system control as opposed to functioning only as a monitor, if workload is low. When workload is high, the relationship is reversed.

Second, an evaluation of the human element in the Hoogovens steel plant (Hoogovens Report, (Note 6)) found that the operator's cognitive tasks changed drastically following large scale automation of the steel milling process. The report (op.cit., p. 14) observed that:

The need for the operator to intervene directly in the process is much reduced, but the requirements to evaluate information and supervise complex systems is higher.

Yet the machine designers did not take this change into account to the detriment of the total systems performance. The system either functioned automatically or passed control of the process to the operator (manual operation). There were no means for or support of the operator's new role as supervisor of an automatic system. In other words, there was an impoverished "cognitive coupling" (Fitter & Sime, 1980) between man and machine. Both of these examples demonstrate that an effective architecture of the MMS cannot be built when the view of the MMS as a cognitive system is ignored.

A third example, which illustrates the breadth of application of the concept of cognitive systems, comes from a study of visual display terminal (VDT) operations. Smith et al. (1981) studied the effects of viewing VDTs on user health complaints and stress levels. They found that "the stress problems ... are not solely related to the VDT viewing, but are related to the whole VDT work system" (p.398). Thus, VDT operation did not affect users directly, but rather indirectly through changes in

job content. The micro-characteristics of VDTs, while a significant factor, were of secondary influence on the user; the primary impact came from the requirements the computer system structure imposed on the user. For clerical workers, VDT use had a negative impact because the man-computer system increased boredom, made jobs more machine-paced, and decreased user control over their work process. In other words, Smith et al. found that the nature of the man-computer system as a cognitive system was the primary influence on the user. This example shows that data content, organization, and display techniques are not the only factors that influence the cognitive structure of a man-machine system. Job content, motivation, group interaction etc. are equally important.

One consequence of the traditional view of an MMS as merely the sum of component tasks is that when errors occur in human performance, designers often respond by automating that particular task or by adding a new piece of machinery to help the human perform better on this particular point. Either way the designer assumes that human performance errors are an intrinsic property of the human element and that the solution lies in isolating a specific function and make it easier for the operator to do it - or relieve him of it completely. However, from the cognitive systems viewpoint, this is an incorrect approach. First, the particular errors may be reduced, but other errors will occur because the total effect of the changes on the underlying cognitive system has not been considered. Second, human performance problems are usually a symptom of poor interface design. This is because the machine design requires that the operator functions in ways that are adapted to the machine (cf. Taylor & Garvey, 1959). As Norman (Note 7, p.39) remarked "forcing people to interact on the machine's terms is not only inconvenient - more importantly, because it is an unnatural mode of interaction, it is a primary cause of human error."

For example, performance problems such as the "getting lost" phenomena (in multiple display man-computer systems) are often attributed to human short-term memory limitations (Robertson et

al., 1981). A typical solution to these problems is to provide memory aids for the user. However, memory limitations are not the cause of the "getting lost" phenomena; they are merely symptoms. Users get lost in complex multiple display nets because the characteristics of the human cognitive system have not been taken into account in system design (Woods, Note 8).

The above examples illustrate the potential usefulness of studying MMSs from a CSE viewpoint. But what exactly are the characteristics of a cognitive system?

WHAT IS A COGNITIVE SYSTEM?

A cognitive system produces "intelligent action", that is, its behavior is goal oriented, based on symbol manipulation and uses knowledge of the world (heuristic knowledge) for guidance. Furthermore, a cognitive system is adaptive and able to view a problem in more than one way. A cognitive system operates using knowledge about itself and the environment, in the sense that it is able to plan and modify its actions on the basis of that knowledge. It is thus not only data driven, but also concept driven. Man is obviously a cognitive system. Machines are, potentially if not actually, cognitive systems. An MMS regarded as a whole is definitely a cognitive system.

One important idea in cognitive psychology and cognitive science is that the concept driven behavior characteristic of intelligent action is produced by means of an internal model or representation of the environment (Johnson-Laird, 1980; Moray (Note 9); Rasmussen, 1976). This model is used for planning and decision making, for formulating messages to be sent, and for interpreting messages received. In relation to the human part of an MMS it is often assumed that they possess a model of the system they are working with, and that their perception of the system as well as their thinking about it is based on (or biased by) their model of the system.

The concept of internal models is far from new. It has been used in relation to the Whorfian hypothesis of linguistic relativity (von Bertalanffy, 1955), to cybernetics (MacKay, 1951 & 1968; Maturana & Varela, 1980), to teaching (Pask, 1970, 1976; Pask & Scott, 1973) and to the analysis of communication in social systems (Bråten, 1973; Bråten & Norlén, 1975). To say nothing of the hypothesis about how even the lowly rat is capable of constructing and utilizing internal representations to solve problems rather than just using trial and error (Tolman, 1948). In the field of MMSs, the power of internal models has often been noted (Ambrozy, 1971; Conant & Ashby, 1970; Hollnagel, 1978; Rasmussen, 1976; Veldhuyzen & Stassen, 1977). As already Craik (1943, p.61) remarked:

If the organism carries a "small-scale model" of external reality and of its possible actions within its head, it is able to try out various alternatives, conclude which is the best of them, react to future situations before they arise, utilize the knowledge of past events in dealing with the present and the future, and in every way to react in a much fuller, safer, and more competent manner to the emergencies which face it.

It seems a logical extension of this idea to say that an explicitly designed artefact may also have a model of its environment, and in particular of its operator. Based on training, experience, instructions, and the nature of the interface, the operator develops an internal model that describes the operation and function of the machine. Similarly, designers build into artificial systems (machines) a model of the user's characteristics although they may not always fully realize that. To distinguish these two models we will refer to the former as the operator's model of the machine and to the latter as the machine's image of the operator (Note 4).

There are several levels to the system's image of the user. First, a machine may possess an image of the physical characteristics of the user. For example, a guitar assumes a user who

is right-handed, who has a certain number of fingers and a given muscular strength. In this example the image of the user is not explicitly stated but is implied by the way in which the machine functions.

On a second level, machines also make assumptions about the operator's cognitive processing capacity. A typical example is that a machine's configuration makes assumptions about how much data the operator can remember. The system designers in the Smith et al. study made an unconscious, implicit assumption that user performance was invariant over a variety of job content factors (level of boredom, externally-paced versus self-paced work, and level of user control over the work process). All systems invariably assume something of the user's cognitive functioning. Unfortunately, the system's image of the user at this level is virtually never explicitly designed to enhance the joint function of man and machine. Rather, like the guitar example, the system's image of the user is only implied or buried in the characteristics and functions of the machine.

This is especially true in complex systems where a number of the system's components that affect the user are designed independently. For example in process control, a variety of instrumentation systems, training programs, procedures, and personnel are all components of the total operational system; yet cross talk among these components can be low to non-existent. Viewing the total operational system as a cognitive system (for instance, what are the problem solving or decision making tasks which must be accomplished in order to handle abnormal events) provides a mechanism to integrate all of the control resources - people, facilities, instrumentation, procedures, and training - into a coordinated system (Rasmussen, 1980a; Woods, Note 10).

Mismatches between man and machine are often the result of the designer's failure to explicitly address the demands a system places on the human element. Engineering psychology has traditionally attempted to produce a match between the system's image and the user on a physical level. One goal of CSE is to

provide designers with the tools necessary to produce a match between the system's image and user characteristics on a mental or cognitive level.

There can be a third level to a system's image of the user. When the machine is also a cognitive system (or mimics functions of the human cognitive system, as for example, decision aids or disturbance analysis systems), the machine domain assumes an image of how two cognitive systems interact in addition to an image of the user's cognitive processing skills and limitations. For example, Fitter & Sime (1980, p.64), discussing the design of computer decision systems, suggest that:

A need exists for improved "cognitive coupling", based on a genuine dialogue between the decision-maker and decision aid. It is necessary for complex automata to be able to explain their own behavior in terms readily understandable to the decision-maker. This is best achieved by attempting to incorporate the user's model of the decision process into the program model.

Ultimately the system's image should not only be explicitly matched to the user's cognitive characteristics, but it should also be dynamic as appropriate. This is because a user may change over time (an increase in job experience), because the nature of the user's task may change dynamically (in process control, the transition from normal to emergency operations), and because there may be different populations of users (programmers versus executives). Examples of dynamic system images range from the simple automatic suppression of background data for experienced users, to the visionary, a computerized decision aid able to recognize and support different user faults identification strategies.

For the present MMSs this may appear to be of minor interest, but it should be noted that several such machines have been designed in Artificial Intelligence, e.g. the PURR-PUSS

(Andrea, 1979) and the Grundy system (Rich, 1979). And CSE certainly has to take this seriously. The goal for design in MMSs should be to make the interaction between the operator and the machine as smooth and efficient as the interaction between two persons. But it is an essential part of human communication that each participant is able continuously to modify his model of the other.

LEVELS OF DESCRIPTION IN MMSs

We have now characterized CSE and also described what is meant by a cognitive system. As the domain is MMSs it is necessary also to restate briefly how CSE fits together with the other types of description which can be given of an MMS.

One point of view of MMSs is the purely technical, which describes the physical structure of the MMS. Another is the functional, concerned with what may be called the functional structure (cf. Rasmussen, 1979). Yet another is the general systems point of view. And still another is the description of the interaction between the operator and the machine, including a description of the operator as such (Note 5).

Descriptions of this interaction have generally been restricted to the physical and physiological levels. The first is exemplified by the anthropometrical guidelines for design of MMSs (e.g. NASA, 1978). The second by traditional human engineering, i.e. descriptions of perception and discrimination, span of attention, power-ergonomics, design of work-space, etc. In recent years this has been extended to cover behavioral aspects although the operator is, at best, considered to be a complicated and quite reliable automaton, the performance of which can be prescribed in minute detail, to fit into the larger pattern of the function of the MMS.

However, it is obvious that the operator is a thinking person and not an automaton. For instance, he not only has to react or respond, but also to make decisions. And these may, especially in so-called critical situations, be radically different from what the designer had in mind - to the extent that the situation has been anticipated at all. Using the distinction between skill-based, rule-based, and knowledge-based behavior (Rasmussen, 1979) descriptions of operators are generally kept to the level of skills. This may be the most frequent type of activity from a statistical point of view, but it is not the most important. It is precisely the cases where the operator must resort to rule-based and knowledge-based behavior that a description of the MMS function becomes interesting - and it is also the situations where current knowledge fails. We simply do not know enough about it, and the little that we know has rarely been formulated in a way that is relevant for MMSs (cf. e.g. Moray, 1981).

The design of MMSs thus generally fails to consider the behavioral aspects of the operator, especially the mental or cognitive functioning. We have claimed that the design of MMSs should consider both the machine and the operator as cognitive systems. And one of the purposes of CSE is to make the machine's image more explicit and intentional. Since the adequacy of this image is crucial for the functioning of the system, it is rational to try to make this image as conspicuous as possible for the designer, and to provide him with concepts and methods for handling it.

HOW ARE COGNITIVE SYSTEMS ENGINEERED?

Engineering a cognitive system revolves around, first, coordinating the system's image of the user with the relevant aspects of the operator's cognitive functioning for the particular application and, second, coordinating the operator's

model of the system with the actual properties of the system. The former is dealt with by the design, the latter normally by instruction and training. Figure 3 is a schematic of how these goals can be met by incorporating cognitive systems engineering into the MMS design process.

Cognitive Task Analysis

First, cognitive analysis is needed to understand the cognitive activities required of the MMS and to fashion those requirements into a state that matches both the technical demands of the application and the operator's functional characteristics in the cognitive domain.

There are many examples of research which identifies user cognitive activities in MMSs. Rasmussen & Jensen (1974) studied the mental procedures used by electronics repairmen in their normal working environment. Woods, Wise & Hanes (1981) and Pew, Miller & Feeher (1981) developed a data base on nuclear power plant operator decision behavior during emergency operations. Hollnagel (Note 11) developed descriptions of operator's mental model of the control relationships among power plant systems (Figure 4). Duncan (1981) and Hunt & Rouse (1981) studied the diagnostic behavior of chemical process control operators and aerospace maintenance workers, respectively, in order to develop better ways to train diagnostic skill. Norman (Note 7 & 1981) and Reason (1975, 1976, 1977, 1979) have developed categorizations of human errors based on analyzing the underlying processing mechanisms cf. also Rasmussen, 1980b. Brooks (1977) and Green (1980) studied ways of using knowledge of the programmer's cognitive activities in the design of more effective computer languages. Card & Moran (1980) performed cognitive task analysis of computer text-editing.

One powerful example of the potential of cognitive task analysis is Rasmussen's work (1981) identifying process control operator's diagnostic strategies based on studies of fault finding behavior. One of several diagnostic search strategies

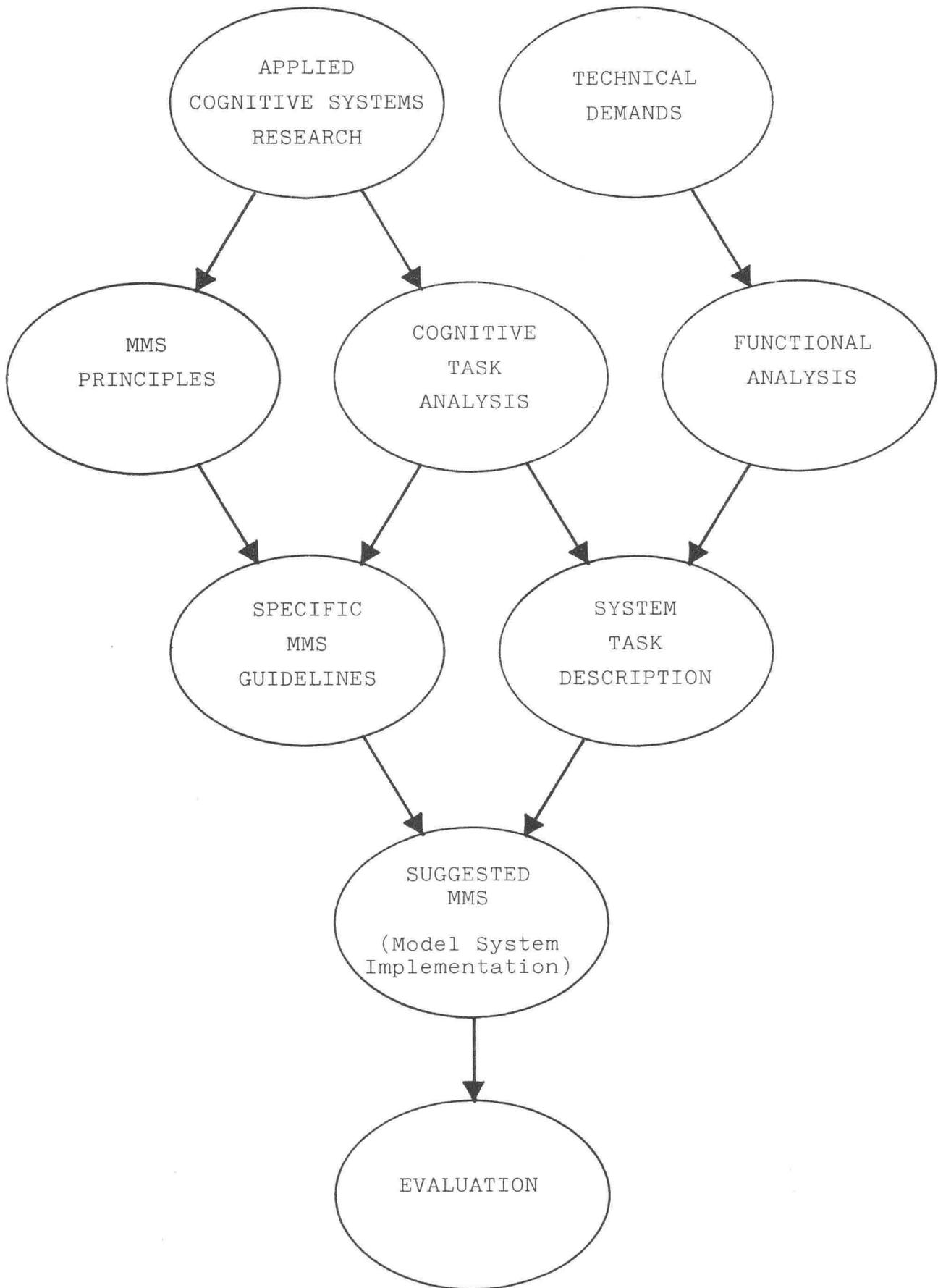
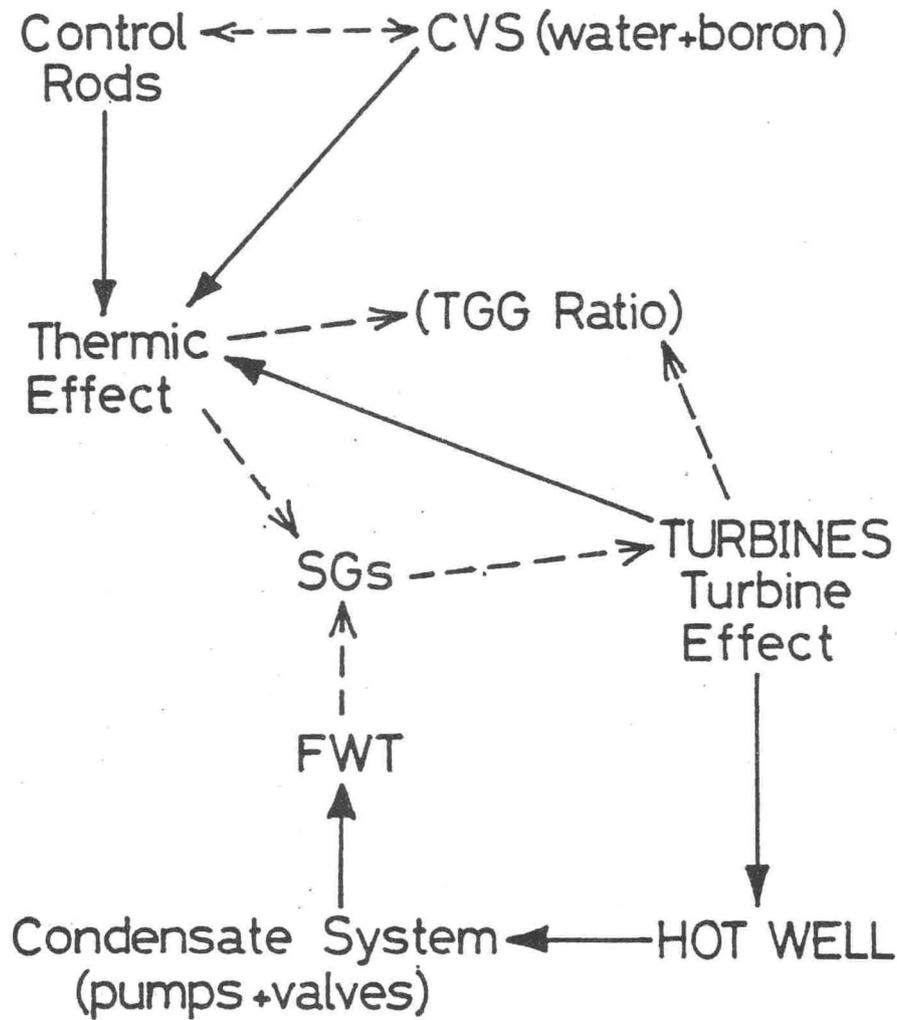


Figure 3. Cognitive systems engineering in the design process.



Subject III.C: Summary of relations and components used in the control of the system.

Figure 4. An associative network representation of a subject's model of a system derived from research simulator data (adapted from Hollnagel, Note 11).

identified by Rasmussen is called topographic search. Topographic search is performed by a good/bad mapping of the system against normal or reference conditions through which the extent of the potentially "bad" field is gradually narrowed down until the problem area is identified. For effective topographic search, an operator utilizes:

- a model of the structure of the system to guide the search; the model varies in level of abstraction (physical components to functional relationships) depending on the specific goals;
- tactical search rules or heuristics;
- a model of the normal operating state of the system;
- relationships among data rather than just the magnitude of variables.

However, nuclear power plant control rooms do not presently support these needs:

- there is only one level of representation of plant state; the operator must construct other levels mentally;
- there is no explicit training or instructions on how to diagnose problems; only the specific signs associated with specific failures are provided;
- there are few indications of normal states, particularly under dynamic conditions (e.g., what is a normal reactor trip); the operator must rely on his memory of reference states;
- the one measurement - one indicator display philosophy does not show relationships between data; the operator must integrate data mentally.

The result is a mismatch between the demand for an efficient diagnosis and the characteristics of the interface, and an

increase of the operator's mental workload with a concomitant increase in the possibilities for errors. The man-machine interface can only be built to support the operator's cognitive activities if these activities are understood. The results of cognitive task analysis is continued in system task descriptions of how the system's characteristics will support the operator's functions as well as the technical demands of the joint MMS.

Man-Machine Principles

Another part of the cognitive systems engineering process (Figure 3) is man-machine principles which describe how characteristics of the interface affect or interact with the user's cognitive functioning. These concepts are called principles because they are not themselves guidelines that can be directly applied; rather they act as meta-guidelines which allow the designer to derive the specific guidelines to incorporate in the design. The principles help specify the MMS goals and the guidelines are derived as a mean to reach those goals.

One example of a principle is the relationship between field of attention and level of abstraction in human cognition (Goodstein & Rasmussen, (Note 12); Rasmussen & Lind, 1981, cf. Figure 5). The point is that there are different levels of representation of a process that vary in level of abstraction (physical components - physical architecture - functional relationships - operational goals) and field of attention (component specific to plant wide). Different tasks typically require different views of the process. While the concept of levels of representation must be incorporated into successful MMSs, the means of implementation are not prescribed. One technique (Goodstein, Note 13) is to provide a recursive set of displays at three levels - goals, functions, and physical systems or components. Each of these levels of displays is in turn represented in terms of goals, functions and physical systems. For example, in a nuclear power plant the safety goal

AGGREGATION/DECOMPOSITION

ABSTRACTION

- PLANT

- PRODUCTION FLOW

- SUB-SYSTEMS

- ABSTRACT FUNCTIONS,
SYMBOLIC FUNCTIONS

- EQUIPMENT

- GENERALIZED FUNCTIONS

- COMPONENTS

- PHYSICAL (MECHANICAL, ELECTRICAL,
CHEMICAL) FUNCTIONS

- PARTS, NUTS AND BOLTS

- PHYSICAL FORM, MATERIAL

TYPICAL COUPLING BETWEEN AGGREGATION AND ABSTRACTION

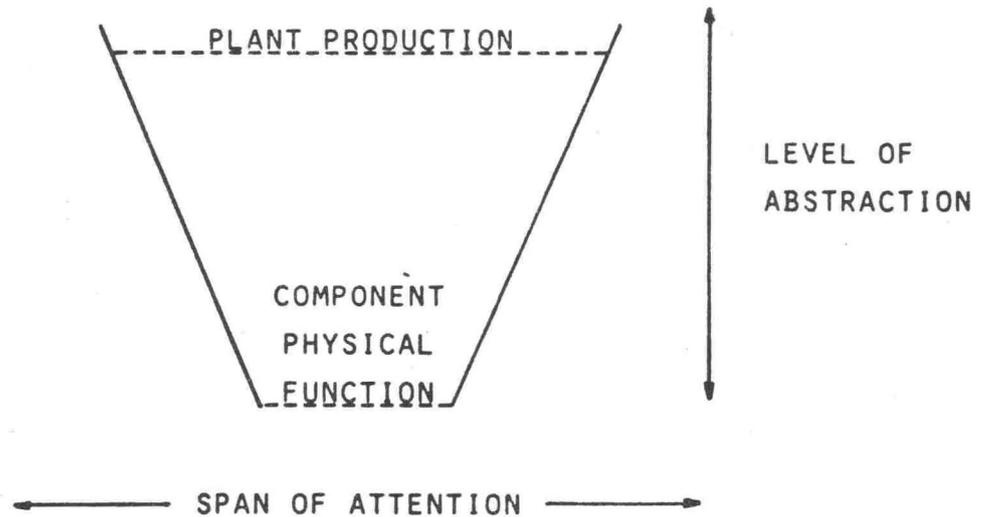


Figure 5. Illustration of the aggregation and the abstraction hierarchy and their typical coupling. (Adapted from Rasmussen & Lind, 1981).

is to maintain barriers to radioactive release. There are certain functions that are necessary and physical systems which support those functions in order to maintain the barriers. Similarly, a particular function, say primary loop circulation, can be taken as the goal of a lower level display which in turn requires that certain functions be met (e.g., seal flow, pumps on) and for which there are various physical components which support each function.

There may be other successful ways to incorporate this and other principles into an interface depending on the entire set of goals to be achieved. In all cases, the specific guidelines are derived as means for building the man-machine concepts specified in the principles into a design.

Evaluating the Suggested Design

The result of the design process is a suggested design or an implementation of the model system. But too often the design process ends here. CSE, on the other hand, explicitly recognized the need for an evaluation of the design, since it is the actual rather than the expected or anticipated consequences of the design which are of importance.

Evaluation a design may take place on several different levels. One type of evaluation is the verification of the design, which essentially is a check of whether the model implementation meets the goals set up in the system task description. Woods & Eastman, (Note 14) is an example of a system design where task descriptions were used to perform this kind of evaluation.

Another type of evaluation is concerned with the validity of the design. The two most important types of validity are the content validity, which is concerned with the similarity between the test conditions and the actual conditions, and the empirical validity, which is concerned with the match between the experimental results and the actual results. A more

penetrating discussion of these matters by be found in Hollnagel, 1981a & b. A schematic representation of the various aspects of the evaluation is shown in Figure 6. The evaluation of a design may, of course, also serve as a part of the cognitive task analysis for future designs. For example, Woods et al., (Note 15) developed a data base on power plant operator's behavior in emergencies while testing the effectiveness of a new computerized operator aid. The process outlined in Figure 3 has been successfully (although imperfectly) used in the design of a computer operator aid for nuclear power plant control rooms (Little & Woods, Note 16; Woods et al., 1981 & Note 15).

FUTURE TASKS FOR COGNITIVE SYSTEMS ENGINEERING

It is characteristic for the behavioral sciences, including the study of MMSs, that their development has been shaped more by external events than by an internal cumulation of knowledge. The development is therefore not continuous but rather takes place in jumps - which not always are jumps forward. This is shown rather dramatically by the very way in which Human Factors Engineering started in the 1940's. The basis was the demands created by the technological development that took place during WW2. This accentuated the need for knowledge about MMSs, and although it was not the historical beginning of the field (which goes back to the early days of the industrial revolution), it at least marked an important turning point. Another important jump was based on the American space program. And at present we are facing the need for a new kind of knowledge about MMSs, which we refer to as Cognitive Systems Engineering. This need has come about both by the rapid evolution of machines which are on the verge of becoming intelligent, as well as by the occurrence of certain events, the Three Mile Island accident for instance, which have

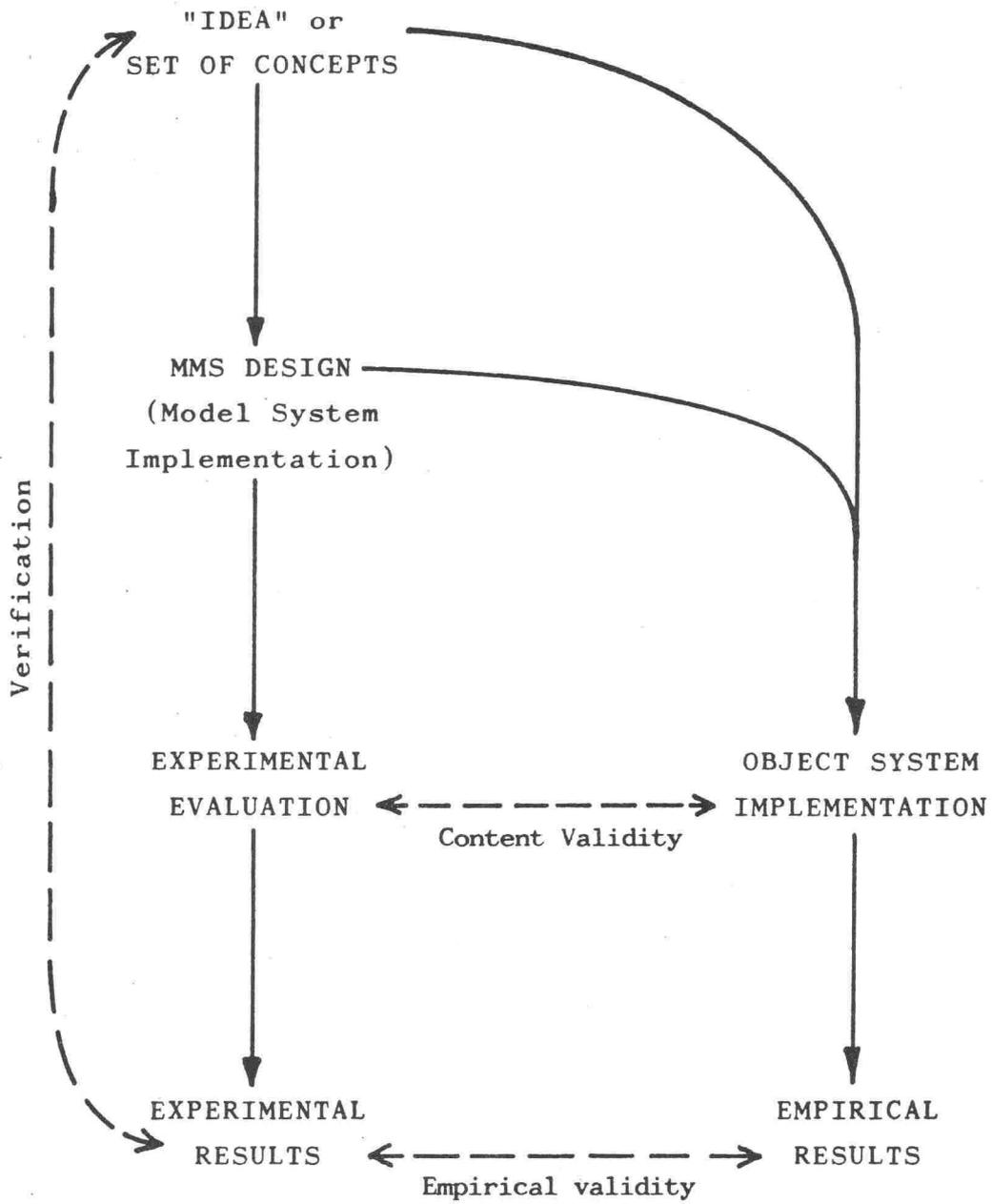


Figure 6. The relation between validity and verification in experimental evaluation (adapted from Hollnagel, 1981b).

demonstrated the deficiency of our present knowledge of MMSs. A jump is therefore required, and in this paper we have tried to describe the direction this jump must take.

If the designer is to build an interface compatible with human cognitive characteristics rather than force the human to adapt to the machine, he must be provided with a clear description of these and with tools and principles that allow him to adapt machine properties to the human. Cognitive systems engineering must develop methods for cognitive task analysis to identify the operator's model of a system, must provide the designer with data on characteristics of human cognition, and must provide the tools to build machines with explicit and appropriate images of the user. While significant steps to meet these goals have been taken in the past few years, considerable research work is needed. This new area of man-machine study is possible because of developments in cognitive psychology, cognitive science, and related disciplines. There exists a growing body of knowledge and techniques about cognitive function to apply to real-world situations. In addition, technological developments are creating a need for understanding the cognitive function of MMSs. Producing a physical match between man and machine is no longer sufficient for effective man-machine function. The characteristics of man as a cognitive system, primarily his adaptability, should not be used as a buffer for bad designs, but rather as beacon for good designs.

NOTES TO THE TEXT

Note 1: The physicalistic fallacy characterizes not only the knowledge about MMSs, but the knowledge in behavioral sciences generally. By saying that this knowledge is of a physicalistic nature we mean that it is modelled on the Natural Sciences, hence assumes that man can be described consistently and adequately in a similar way. This is, however, an untenable assumption, cf. the more thorough discussion in Hollnagel (Note 1).

Note 2: It would be more proper to talk about the psychological functioning of the operator, since cognition is only part of that. Such factors as motives, emotions, affects, attitudes, aspirations, etc., are obviously important in shaping the performance of the operator. In order to minimize the confusion we shall talk only about the cognitive functioning of the operator, but the reader must remember that this is used as generic term for all the mental processes, and not just for those which are within the domain of rational thinking.

Note 3: We do not at this point want to enter a discussion of whether machines as such can be intelligent, since this rapidly leads into a quagmire of unresolved philosophical controversies. We simply want to state that from the point of view of the so-called naive observer - a person not concerned with philosophical or epistemological problems - the machines of today appear to be able to behave in an intelligent way as that word is normally used. And we simply have to acknowledge the fact that in a specific context a person may treat a machine as if it was intelligent, cf. e.g., McCorduck, 1979 and Weizenbaum, 1976.

Note 4: As used here, the terms are in disagreement with the usage suggested by Norman (Note 4). He calls the operator's model of the machine for a System Image, while the corresponding model of the operator is called the Model of the User. This Model of the User is, however, specified as a model of the information processing structures of the user, i.e. essentially a model of the assumed cognitive mechanisms. But the machine's image of the operator need not contain a specification of his information processing system, since this is just one way of looking at the operator. We have chosen to use the term "image" to refer to the system's model of the user because image connotes a built-in, fixed characteristic. The term "model" is used to refer to the user's mental model of the system because the user's model can change as a function of experience, training, and the characteristics of the system interface.

Note 5: In addition to these points of view, further instances may be given once the exact nature of the MMS is known. If, for instance, it is a nuclear power plant, descriptions of the system with respect to e.g., radiation, risk analysis, economy, public attitudes, etc., become important as separate points of view. Although both authors have worked mainly with nuclear MMSs, we do not want to restrict the idea of CSE to that, hence try to avoid specific references in the text.

REFERENCE NOTES

- (1) Hollnagel, E. (1981). What we do not know about man-machine systems. Roskilde, Denmark: Risø National Laboratory, Electronics Department N-40-81.
- (2) Mallory, K., Fleger, S., Johnson, J., Avery, L., Walker, R., Baker, C. & Malone, T. (1980). Human engineering guide to control room evaluation. Draft report, Nureg/Cr--1580.
- (3) Hollnagel, E. (1982). Cognitive psychology: The American and European approaches. London: Academic Press Ltd. (in press).
- (4) Norman, D. A. (1981). Steps towards a cognitive engineering: System images, system friendliness, mental models. San Diego, California: University of California, Department of Psychology and Program in Cognitive Science. (Draft.)
- (5) Kisner, R. A., Fullerton, A. M., Frey P. R. & Dougherty, E. M. (1981). A taxonomy of the nuclear plant operator's role. Oak Ridge, Tennessee: Oak Ridge National Laboratory,
- (6) Human factors evaluation. Hoogovens No. 2 hot strip mill. (1976). London: British Steel Corporation/Hoogovens, FR251.
- (7) Norman, D. A. (1980) Errors in human performance. San Diego, California: Center for Human Information Processing.
- (8) Woods, D. D. (1981). Principles of visual momentum in the design of computer-based display systems. Pittsburgh: Westinghouse Research and Development Center 82-C57-HUBUS-R1.
- (9) Moray, N. (1981). Human information processing and supervisory control. Massachusetts Institute of Technology, Industrial Liason Program.
- (10) Woods, D. D. (1981). Human factors analysis in nuclear power plant operations. Paper presented at the Fourth Symposium on Training of Nuclear Facility Personnel, Gatlinburg, Tennessee, April 1981.

- (11) Hollnagel, E., (1981). Report from the third NKA/KRU experiment: The performance of control engineers in the surveillance of a complex process. Roskilde, Denmark: Risø, Electronics Department N-14-81 (NKA/KRU-P2(81)36).
- (12) Goodstein, L. P. & Rasmussen, J. (1980). Man-machine system design criteria in computerized control rooms. Roskilde, Denmark: Risø, Electronics Department, N-7-80, (NKA/KRU-P2(80)23).
- (13) Goodstein, L. P. (1981). Overview on control room design. Roskilde, Denmark: Risø, Electronics Department, (NKA/KRU-P2(81)42).
- (14) Woods, D. D. & Eastman, M. C. (1981). Human factors evaluation of the technical support complex display systems. Pittsburgh: Westinghouse Research and Development Center, 81-1C57-CONRM-R1.
- (15) Woods, D. D., Wise, J. A. & Hanes, L. F. (1981). An evaluation of safety parameter display systems. Palo Alto, California: Electric Power Research Institute, Research Project 891-5.
- (16) Little, J. L. & Woods, D. D. (1981). A design methodology for the man-machine interface in nuclear power plant emergency response facilities. Pittsburgh: Westinghouse Research and Development Center, 81-1C57-CONRM-P1.

REFERENCES

- Allport, D. A. (1980). Patterns and actions: Cognitive mechanisms are content-specific. In G. Clarton (Ed.), Cognitive psychology: New directions. London: Routledge & Kegan Paul.
- Ambrozy, D. (1971). On man-machine dialogue. International Journal of Man-Machine Studies, 3(4), 375-383.
- Andrea, P. M. (1979). Thinking with the teachable machine. London: Academic Press.

- Beer, S. (1964). Cybernetics and management. New York: Science Editions.
- Brooks, R. (1977). Towards a theory of the cognitive processes in computer programming. International Journal of Man-Machine Studies, 9, 737-751.
- Bråten, S. (1973). Model monopoly and communication: Systems theoretical notes on democratization. Acta Sociologica, 16(2), 98-107.
- Bråten, S. & Norlén, U. (1975). Description and models of a simulation of communication model. In U. Norlén (Ed.), Simulation model building. New York: John Wiley.
- Card, S. K. & Moran, T. P. (1980). Computer text-editing: An information processing analysis of a routine cognitive skill. Cognitive Psychology, 12, 32-74.
- Conant, R. C. & Ashby, W. R. (1970). Every good regulator of a system must be a model of that system. International Journal of Systems Science, 1(2), 89-97.
- Craik, K. (1943). The nature of explanation. Cambridge: Cambridge University Press.
- Duncan, K. D. (1981). Training for fault diagnosis in industrial process plants. In J. Rasmussen & W. B. Rouse (Eds.), Human detection and diagnosis of system failures. New York: Plenum Press.
- Edwards, W. (1954). The theory of decision making. Psychological Bulletin, 51(4), 380-417.
- Edwards, W. (1961). Behavioral decision theory. Annual Review of Psychology, 12, 473-498.
- Ephrath, A. R. & Young, L. R. (1981). Monitoring vs. man-in-the-loop detection of aircraft control failures. In J. Rasmussen & W. B. Rouse (Eds.), Human detection and diagnosis of system failures. New York: Plenum Press.
- Feigenbaum, E. A. (1978). The art of artificial intelligence - Themes and case studies of knowledge engineering. AFIPS Conference Proceedings, 47, 227-240.
- Fitter, M. J. & Sime, M. E. (1980). Responsibility and shared decision-making. In H. T. Smith & T. R. G. Green (Eds.), Human interaction with computers. London: Academic Press.
- Green, T. R. G. (1980). Programming as a cognitive activity. In H. T. Smith and T. R. G. Green (Eds.), Human interaction with computers. London: Academic Press.

- Halpin, S. M., Johnson, E. M. & Thronberry, J. A. (1973). Cognitive reliability in manned systems. IEEE Transactions on Reliability, R-22, 165-169.
- Hollnagel, E. (1978). Qualitative aspects of man-machine communication (Risø-M-2114). Risø National Laboratory, Roskilde, Denmark: Electronics Department, (NKA/KRU-P2(78)5).
- Hollnagel, E. (1981a). Verification and validation in the experimental evaluation of new designs for man-machine systems (Risø-M-2300). Risø National Laboratory, Roskilde, Denmark: Electronics Department, (NKA/LIT-3(81)108).
- Hollnagel, E. (1981b). The methodology of man-machine systems: Problems of verification and validation (Risø-M-2313). Risø National Laboratory, Roskilde, Denmark: Electronics Department, (NKA/LIT-3(81)106).
- Hunt, R. M. & Rouse, W. B. (1981). Problem-solving skills of maintenance trainees in diagnosing faults in simulated power plants. Human Factors, 23, 317-328.
- Janis, I. L. & Mann, L. (1977). Decision making. New York: The Free Press.
- Johnson-Laird, P. N. (1980). Mental models in cognitive science. Cognitive Science, 4, 71-115.
- Kolers, P. A. (1979). A pattern-analyzing basis of recognition. In L. S. Cermak & F. I. M. Craik (Eds.), Levels of processing in human memory. Hillsdale, New Jersey: Lawrence Erlbaum Associates.
- Kubovy, M. & Pomerantz, J. R. (1981). Perceptual organization. Hillsdale, New Jersey: Lawrence Erlbaum Associates.
- MacKay, D. M. (1951). Mindlike behavior in artefacts. The British Journal for the Philosophy of Science, 2(6), 105-121.
- MacKay, D. M. (1968). Towards an information-flow model of human behavior. In W. Buckley (Ed.), Modern systems theory for the behavioral scientist. Chicago: Aldine Publishing Company.
- March, J. G. & Simon, H. A. (1958). Organizations. New York: John Wiley.
- Maturana, H. R. & Varela, F. J. (1980). Autopoiesis and cognition. Dordrecht, Holland: D. Reidel Publishing Company. (Boston Studies in the Philosophy of Science, Vol. 42.)

- McCorduck, P. (1979). Machines who think. San Francisco: W. H. Freeman.
- MIL-STD-1472C, (1981). Human engineering design criteria for military systems, equipment and facilities.
- Moray, N. (1981). The role of attention in the detection of errors and the diagnosis of failures in man-machine systems. In J. Rasmussen & W. B. Rouse (Eds.), Human detection and diagnosis of system failures. New York: Plenum Press.
- NASA, (1978). Anthropometric source book. Yellow Springs, Ohio: NASA Reference Publication 1024.
- Neisser, U. (1976). Cognition and reality. San Francisco: W. H. Freeman.
- Norman, D. A. (1981). Categorization of action slips. Psychological Review, 88, 1-15.
- Norman, D. A. & Bobrow, D. G. (1976). On the role of active memory processes in perception and cognition. In C. N. Cofer (Ed.), The structure of human memory. San Francisco: W. H. Freeman.
- Palmer, S. E. (1975). Visual perception and world knowledge: Notes on a model of sensory-cognitive interaction. In D. A. Norman, D. E. Rumelhart & LNR Research Group (Eds.), Explorations in cognition. San Francisco: W. H. Freeman.
- Pask, G. (1970). Cognitive systems. In P. L. Garvin (Ed.), Cognition: A multiple view. New York: Spartan Books.
- Pask, G. (1976). Conversational techniques in the study and practice of education. British Journal of Educational Psychology, 46, 12-25.
- Pask, G. & Scott, B. C. E. (1973). CASTE: A system for exhibiting learning strategies and regulating uncertainties. International Journal of Man-Machine Studies, 5, 17-52.
- Pew, R. W., Miller, D. C. & Feeher, C. E. (1981). Evaluation of proposed control room improvements through analysis of critical operator decisions. Palo Alto, California: Electric Power Research Institute, Research Project 891, NP-1982.
- Rasmussen, J. (1976). Outlines of a hybrid model of the process plant operator. In T. B. Sheridan & G. Johannsen (Eds.), Monitoring behavior and supervisory control. New York: Plenum Press.

- Rasmussen, J. (1979). On the structure of knowledge - A morphology of mental models in a man-machine system context (Risø-M-2192). Risø National Laboratory, Roskilde, Denmark: Electronics Department.
- Rasmussen, J. (1980a). The human as a systems component. In T. H. Smith & T. R. G. Green (Eds.) Human interaction with computers. London: Academic Press.
- Rasmussen, J. (1980b). What can be learned from human error reports. In K. Duncan, M. Gruneberg & D. Wallis (Eds.), Changes in working life. New York: John Wiley & Sons.
- Rasmussen, J. (1981). Models of mental strategies in process plant diagnosis. In J. Rasmussen & W. B. Rouse (Eds.), Human detection and diagnosis of system failures. New York: Plenum Press.
- Rasmussen, J. & Jensen, A. (1974). Mental procedures in real life tasks: A case study of electronic trouble shooting. Ergonomics, 17, 193-307.
- Rasmussen, J. & Lind M. (1981). Coping with complexity (Risø--M-2293). Risø National Laboratory, Roskilde, Denmark: Electronics Department.
- Reason, J. T. (1975). How did I come to do that? New Behaviour, April 24.
- Reason, T. J. (1976). Absent minds. New Society, November 4.
- Reason, T. J. (1977). Skill and error in everyday life. In M. Howe (Ed.), Adult learning. London: Wiley.
- Reason, T. J. (1979). Actions not as planned. In G. Underwood & R. Stevens (Eds.), Aspects of consciousness. London: Academic Press.
- Reisner, P. (1981). Using a formal grammar in human factors design of an interactive graphics system. IEEE Transactions on Software Engineering, SE-7, 229-240.
- Rich, E. (1979). User modelling via stereotypes. Cognitive Science, 3, 329-354.
- Robertson, G., McCracken, D. & Newell, A. (1981). The ZOG approach to man-machine communication. International Journal of Man-Machine Studies, 14, 461-488.

- Rouse, W. B. (1977). Human-computer interaction in multitask situations. IEEE Transactions on Systems, Man and Cybernetics, SMC-7(5), 384-392.
- Runeson, S. (1977) On the possibility of "smart" perceptual mechanisms. Scandinavian Journal of Psychology, 18, 172-179.
- Sime, M. & Fitter, M. (1978). Computer models and decision making. In P. B. Warr (ed.) Psychology at Work (2nd ed.). Harmondsworth: Penguin.
- Smith, M. J., Cohen, B. G. F., Stammerjohn, L. W. & Happ, A. (1981). An investigation of health complaints and job stress in video display operations. Human Factors, 23, 387-400.
- Taylor, F. V. & Garvey, W. D. (1959). The limitations of a "procustean" approach to the optimization of man-machine systems. Ergonomics, 2, 187-194.
- Taylor, F. W. (1911). The principles of scientific management. New York: Harper & Row.
- Tolman, E. C. (1948). Cognitive maps in rats and men. Psychological Review, 53, 189-208.
- Vaughan, W. S. Jr. & Mavor, A. S. (1972). Behavioural characteristics of men in the performance of some decision-making task components. Ergonomics, 15(3), 267-277.
- Veldhuyzen, W. & Stassen, H. G. (1977). The internal model concept: An application to modelling human control of large ships. Human factors, 19(4), 367-380.
- Von Bertalanffy, L. (1955). An essay on the relativity of categories. Philosophy of Science, 22(4), 243-263.
- Weizenbaum, J. (1976). Computer power and human reason. San Francisco: W. H. Freeman.
- Woods, D. D., Wise, J. A. & Hanes, L. F. (1981). An evaluation of nuclear power plant safety parameter display systems through the analysis of operator decision behavior during simulated multiple failure accidents. Proceedings of the Human Factors Society, 25th Annual Meeting, October, 1981.

Risø - M - 2330	Title and author(s) COGNITIVE SYSTEMS ENGINEERING New Wine in New Bottles E. Hollnagel (Risø National Laboratory) D. D. Woods (Westinghouse Research and Development).	Date February 1982 Department or group Electronics Group's own registration number(s) R-3-82
	pages + tables + illustrations	EH/AME
	Abstract This paper presents a new approach to the description and analysis of complex man-machine systems, called Cognitive Systems Engineering. In contradistinction to the traditional approaches to the study of man-machine systems (MMSs) which mainly operate on the physical and physiological level, CSE operates on the level of cognitive functions. Instead of viewing an MMS as decomposable by mechanistic principles, CSE introduces the concept of a <u>cognitive system</u> : an adaptive system which functions using knowledge about itself and the environment in the planning and modification of actions. Operators are generally acknowledged to use a <u>model</u> of the system (machine) they are working with. But similarly the machine has an <u>image</u> of the operator, whether implicit or explicit. The designer of an MMS must recognize this, and strive to obtain a match between the machine's image and user characteristics on a cognitive level, rather than just on a physical level. The paper gives a presentation of what cognitive systems are, and of how CSE can contribute to the design of an MMS, from the cognitive task analysis to the final evaluation.	Copies to
Available on request from Risø Library, Risø National Laboratory (Risø Bibliotek), Forsøgsanlæg Risø), DK-4000 Roskilde, Denmark Telephone: (03) 37 12 12, ext. 2262. Telex: 43116		