Modeling of Human-Machine Systems
A Challenge for Systems Analysis

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ABSTRACT

Recent industrial accidents have proved the need for considering also human acts influencing the safety of industrial installations. An understanding of human errors relies on an understanding of the cognitive mechanisms of human decision making. Different attempts have been made to build models of the human operator, but the models have mostly concentrated on single individuals and isolated tasks. The models developed are also descriptive and are not very useful in guiding the design of new systems. At present there is no model, by which accurate predictions of the performance of a socio-technical system can be given. It is necessary to develop new modeling techniques, before it is possible to model the human parts of industrial installations to such a degree of accuracy that it is possible to predict their safety. The chapter discusses afferent modeling approaches, their advantages and disadvantages in providing guidance for designing future systems. The chapter discusses also some general requirements on the modeling methods of human-machine systems.

1. INTRODUCTION

Early insights in the necessity of considering the human as a part of a system was, obtained during the second world war in the design of weapons systems. Development in the avionics field during the fifties displayed the importance of the dynamics of the pilot as a controller for the in-flight performance of aircraft. Research in the sixties produced many important results on the design of human-machine interfaces, which have been used in the design of the flight decks of present aircraft [1]. The developed ideas dissipated however only slowly to the process industries, in spite of an early understanding of the problems involved [2].

In spite of the slow utilization of human factors principles in the design of industrial control rooms, the nuclear industry got involved early. The obvious reason was the need for ensuring the safety of the nuclear power plants by avoiding human errors. The WASH-1400 report included an analysis of human errors possible in operating a set of buttons. The concern for human factors in the nuclear power plants led to a classic study of control room solutions in five operational plants [3]. In the report, critics were expressed towards the practical control room design solutions of the plants investigated.

The accident at the TMI-2 plant near Harrisburg in 1979, was the triggering event for much more activities in the human factors field. The accident commission identified three generic areas of deficiencies; control room design, operating procedures, and operator training. The accident initiated many different upgrading actions in the opera-

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tional plant and the plants under construction. New regulations and improved guidelines for the control room design have been developed and it is now common practice to make a human factors analysis of the control room solutions as a part of the design project [4].

The actions of the nuclear industry to the deficiencies revealed in the TMI-accident have been straightforward and considerable improvements of the safety of the nuclear plants have been obtained. The awareness that human errors have an important contribution to the safety of the nuclear power plant, has also introduced a deeper discussion of the human factors issues. The difficulty in ensuring the safety of complex socio-technical systems has been discussed in the frame of "normal" accidents [5]. Technological accidents (Bhopal, Challenger, Chernobyl, Sandoz, Piper Alfa, etc.) have also demonstrated many difficulties involved in the design and operation of complex systems. One may even conjecture that accidents are necessary to reveal-deficiencies in the way technical systems are designed and operated.

Systems analysis has a record of success in improving the, performance of technical systems by using different models. The modeling of socio-technical systems implies that suitable models are constructed also for the human part of the system. Unfortunately it is very difficult to build reliable and valid models for describing how single or groups of humans will behave in different situations. Models available are qualitative and descriptive, which means that they hardly can be used for comparing relative merits of design alternatives. To meet the demands of an improved safety for the increasingly complex industrial installations, there is a need for developing new methods and tools, which would make it possible to model an entire socio-technical system within one framework.

2. THE SYSTEMS ANALYSIS PARADIGM

Systems analysis can be seen as the process of observing, modeling, and optimizing a system under consideration [6]. The target system is observed and experimented with and a mathematical model of the system is built. The mathematical model is used to optimize the performance of the target system by comparing alternate designs. A formulation of a mathematical model will usually proceed according to the following phases:

- definition of the purpose of the modeling exercise,
- definition of the scope of the model,
- definition of the model variables,
- establishment of relationships between variables,
- formulation of model equations,
- validation and verification of the model, and
- use of the model for the intended purpose.

The purpose of the modeling exercise is to set the required scope of the model and thus its region of validity. The definition of the modeling scope includes a separation between the model and its environment and a definition of the required accuracy of the model. A selection of model variables to be included and their relationships expands the modeling from a qualitative framework to quantified causal influences to be expressed as mathematical equations. The validation and verification phase aims at a demonstration of the correctness of the model and should be done with experimental data.

It is common to make a separation between the structure of the model and the parameters of the model. Some parameters can be obtained by independent assessments of crucial system parameters. The model structure should ideally reflect causal influences between variables of the real system. For the calculation of system parameters from experimental data many techniques have been developed, but it is not always possible to find a parameter estimation method with the implied model structure of the causal interactions. Observational and experimental data are always related to more or less explicitly formulated models.

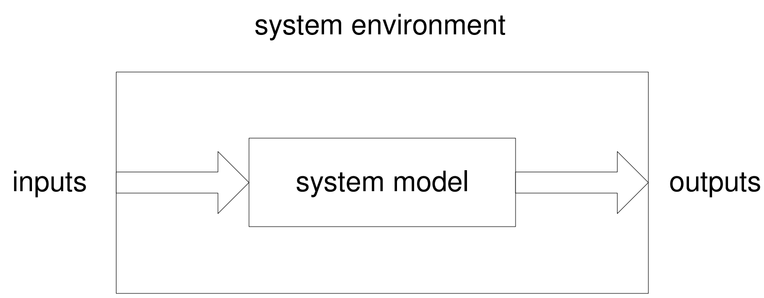

Figure 1: The separation between the system and its environment. Interactions between the system and its environment are carried through the inputs and outputs of the system.

A model of a system and how it is connected to the environment can be illustrated with Figure 1. There are three different problems of systems analysis that can be identified. The first problem is an identification problem, i.e., a model is sought. The second problem is to search for the output of the system (simulate the system) when the model is given. The third problem is to search for an input (a control problem) which will give a wanted output. Any system theoretic problem is implicitly a control problem, because one is usually interested in finding an input giving the most favorable output.

The three problems of systems analysis are suggesting three subproblems connected to the existence of a solution for the primary problem. The identifiability of the parameters connected to a certain model structure is depending on the extent input signals are exercising functional modes of the system under consideration. The existence of unambiguous output signals for a certain system model and given input signals depends on the observability of the system. The existence of an input, which will generate a specified output, is connected to the controllability of the system.

3. DESIGN AND OPERATION OF INDUSTRIAL PROCESSES

Large industrial installations, such as nuclear power, offshore and chemical plants rely on an intricate web of supporting systems encompassing design, construction, operation and maintenance. The design and construction of an industrial installation can typically involve a combined effort of several, tern-thousands of working hours and a total cost of some billion US dollars. During the design and construction project, several hundred thousand different items are to be designed, manufactured; installed, tested, and documented. Special organizations and tools are necessary only to coordinate and keep track of all different items and activities in building a large plant. There is a potential of using computer aided design systems to reach a high design quality [7].

The safety of the large industrial installations relies on a tradition of design and management which have evolved during a long time. New concepts are introduced in an evolutionary manner and proven design is a key requirement. The strive for a higher efficiency of processes and plants, however, brought forward an increasing complexity of the installations [8]. The complexity makes it more difficult to avoid design and operational errors and they are becoming more costly due to the increased size of the installations. Rapid technological development has also introduced new solutions with short lead times, with the possibility that factors contributing to the safety have not been properly considered before the new solution is put into operation.

The operating of modern industrial installations depends to a large extent on automation, which means that the necessary control actions to maintain the operational state of the process is handled with automatic control systems. The automatic control can functionally be divided into the following parts:

- stabilizing control of single variables,
- coordinating control for plant subprocesses,
- start-up and shutdown automatics,
- safety systems, and
- interlocks.

The stabilizing control of single variables makes it possible for the operators to concentrate on operating the plant without an excessive demand on their alertness in the task of keeping thousands of plant variables within their operational limits. The coordinating control makes it possible for the operators to execute complicated maneuvers in a coordinated way without an excessive demand on the number of hands and eyes to be used. The start-up and shutdown automatics take the plant through a series of coordinated state changes of subprocesses, which would be impossible to carry out manually. The safety systems should always be automated, because it is not possible to rely on human detection and actions for the most critical operations. The interlocks are designed to make the plant systems forgiving by locking out actions from the operator in certain plant conditions.

The process information system is usually treated as a part of the automation system, although it is functionally a separate system. The information system and the remotely controlled process components make it possible for the operators to operate the process from a centralized control room. An alarm system is usually connected to the plant information system, by which important changes in the plant variables are signaled to the operator. The alarm system maps it easier for the operator to detect important changes in the process. The information-systems of the industrial plants of today are usually realized using computers and visual display units (VDU).

The division of the tasks between the control room- operator and the automation system depends on the process, on traditions, and on staffing policies. For many processes there is a minimum level of automation needed to make it possible for a specified control room staff to run the plant. Ideally, increased automation will ideally make the plant easier to operate, but has the drawback of increasing the complexity of the plant. There is also a tendency of automation designers to automate only well-structured tasks and to leave more complicated tasks to the operator [9]. Increased automation will in general increase the skill requirements of the operators.

The strict requirements for safety have introduced several precautions both in the design and the operation of the plants. The plants are regulated by competent authorities and operational experience is collected systematically. The plants are built using a "defense in depth" concept, according to which the plant should withstand several degradations without any danger for the environment. The principles for how the industry is handling safety can be seen as a multi-level hierarchical control system, where both feedback and feedforward control is used to ensure that safety targets can be maintained [10].

4. LESSONS FROM RECENT ACCIDENTS

Event-trees are used to model the causality of interconnected events in the handling of industrial safety (Fig. 2). Any event is caused by one or several precursors (secondary events) and has several consequences. If it is possible, e.g., by the design of the technical system, to prevent a specific event from occurring it is also possible to prevent other unwanted events downstream in the causal chains. The direction towards the consequences of the events gives the importance of any single event concerning safety. The direction towards the causes indicates possible remedies for unwanted events. An analysis of accidents and incidents in terms of causes and possible consequences provides the background necessary to increase our understanding of factors that decrease the safety of the plants.

Available accident reports indicate that 30-70% of accidents are caused either directly or indirectly by human errors. There are differences among industrial areas, but they suggest variations in the reporting systems rather than real differences in operational experience. In the analysis, the human factor should always be analyzed in more detail to reveal system deficiencies contributing to the error. Deficiencies in the control room design, errors in the operating procedures and inappropriate training may then show to have been causing the error (Figure 3). The deficiencies may even suggest generic problems in the management of safety in the design and operation of the plants.

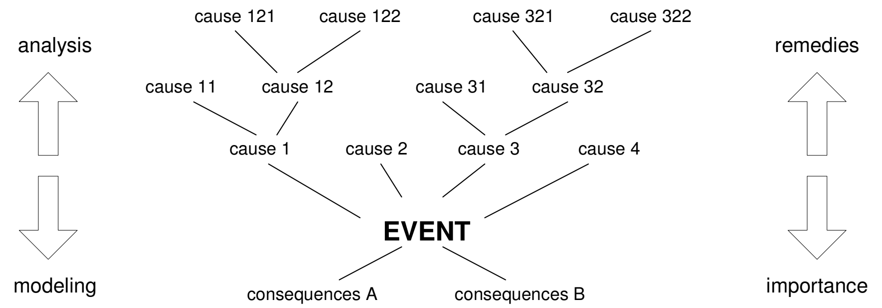

Figure 2: An accident can be seen as a chain of events connected by arcs of causation. A specific accident can be avoided by breaking the chain of causation, e.g. by improvements in the system.

An analysis of recent industrial accidents -reveals similarities, but, also important differences. The chain of events is triggered by a complicated interaction of seemingly isolated technical .failures and human errors. There are several different groups of people involved and the onset of the accident usually takes a long time. There is a component of goal ambiguity, where productivity goals interact with safety goals. In many accidents the operators have not correctly interpreted the seriousness of the situation. There are also communication problems between key actors during the chain of events. There have usually been earlier warnings, but responsible persons and organizations have not been reacting properly on the experience. However, the accidents have also introduced some genuine component of surprise, although the deficiencies found have been well understood,

There are also important differences in the accidents. Different industries are handling similar safety problems very differently. There are also differences in safety principles between different companies and even differences within the same, company. There seem to be important differences between different countries, which may suggest the importance of a cultural tradition in how industrial safety is handled. In creating an understanding of how the socio-technical systems are handling the safety, it is necessary to investigate the reasons for the differences observed. In the nuclear industry these observations have led to an increased stress on the safety culture of the plants [11].

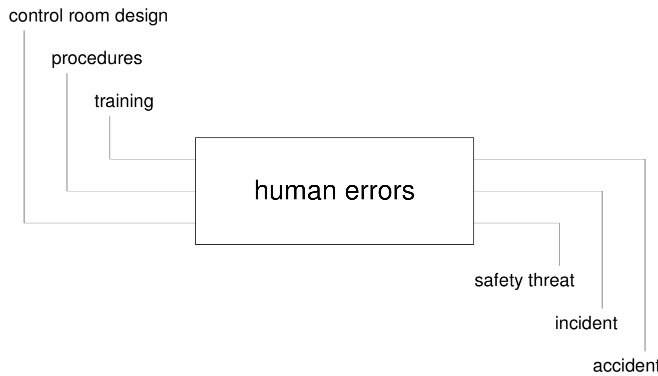

Figure 3: Human errors can lead to safety threats, incidents and even accidents, but it is important to remember that the human errors also have their own causation mechanisms in system deficiencies.

5. MODELING THE HUMAN OPERATOR

Psychological research has been building models of human behavior for a long time. The models are, however, often descriptive and not suited for making predictions of resulting system performance. The models are therefore difficult to use in guiding the design of new industrial plants. Other modeling approaches have been more closely connected to the engineering disciplines and models have been developed, which have had an impact also on the design of the technical systems.

The approach used for the modeling of the human operator is depending on his/her task. The human as a part of a control loop has been modeled using control theory. Humans have been shown to have good abilities in adapting their behavior to the dynamics of the controlled system. The task of detecting a deviation from a target value in a set of monitored variables has successfully been modeled using queuing theory. Supervisory control is combining many simple control tasks, where the operator should be able to detect, interpret, and correct deviations from specified targets [12].

One approach for describing the behavior of operators of complex industrial processes has been discussed in the work of Jens Rasmussen. The task of the control room operator can be described as consisting of one path of analysis and one path of execution with several possibilities for a rapid transfer between states of knowledge [13]. His notion of skill, rule, and knowledge-based behavior has been widely adopted [14]. Another concept which helps the operators in their understanding of the process is connected to abstraction and aggregation [15]. Rasmussen has also discussed the utilization of different strategies for the search of the causes to some specific disturbance of the process [16].

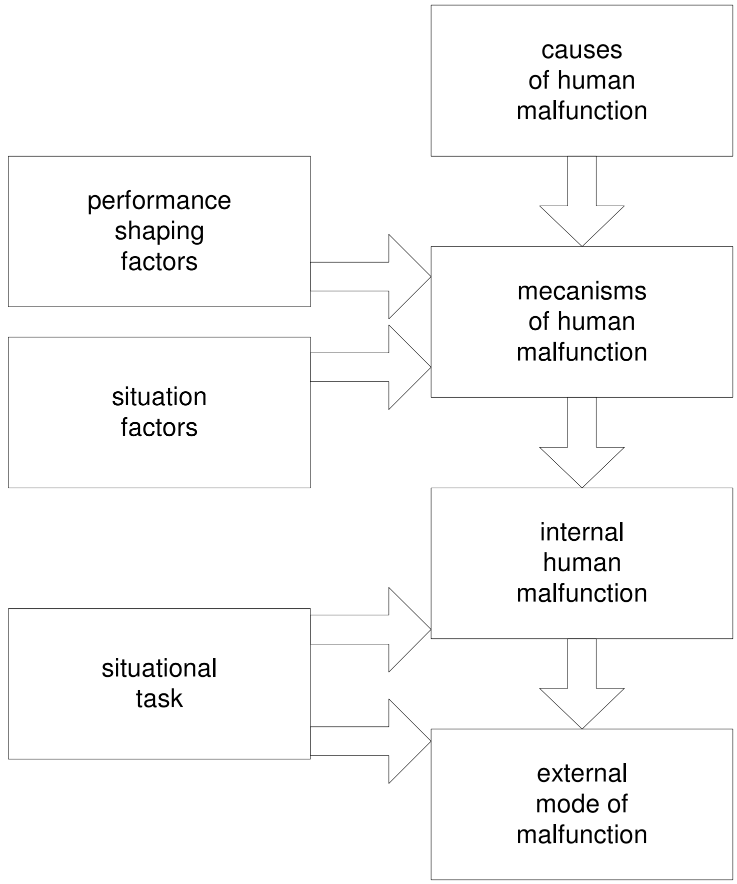

Figure 4: A more refined model of the emergence of human errors.

Considerable efforts have been directed toward the understanding and modeling of human errors. One specific need in this work is connected to the probabilistic safety assessment (PSA) studies which are aiming at assessing the overall safety of a specific plant [17]. Including human errors in the PSA models implies that the probability of some specific human error should be estimated. Presently available models are based on subjective judgment and the model predictions are therefore hard to prove reliable and valid [18]. One qualitative model of human errors is based on the division into slips and mistakes, where a slip is a genuine error and a mistake indicates an error of intention [19]. In more refined models of human error it has been proposed that the causal mechanisms of their occurrence be considered (Figure 4) [20].

Operators are apparently building up different internal models of the process they are operating. The internal models enable the operators to predict future developments of the state of the process and by that to select efficient strategies for the solution of emerging problems. One part of the internal models is formed during the process training and another part during the actual operation of the process. The internal models are an important part of any model describing the behavior of human operators because they-are governing the collection and interpretation of information from the process. In the case, the internal models of the operator do not correctly describe the dynamics of the process, it is very likely that errors will be committed.

There have been many experiments comparing the performance of a human decision maker with a mathematically optimal decision maker. The results have shown that even well trained human decision makers may have problems in performing optimally, Many explanations have been given, but evidently, the 'utility functions` humans are using in their decision making tasks do not always correspond to the mathematically defined utility functions. One approach for improving the performance has `been to build specialized tools to support the decision makers in their tasks.

The intent of the human decision maker plays an important role as a causation mechanism for the actions taken. This means that for the modeling purposes it would be necessary to include intent and its influence on and dependence of other variables. There have been attempts to assess the intent of decision makers by the definition of a subjective utility function, but intent is not a measurable variable in the same sense as pressure, temperature, and flow. Self-reference is another mechanism to be modeled because human are developing images (models) of themselves which are influencing their behavior in different situation. There are many speculative mechanisms of causation which have to be included if a covering description of the human decision maker is attempted.

6. MODELING ORGANIZATIONS

The control room operator has traditionally been the person who has been getting the most attentions, when the performance of the process is considered. It is however equally important to consider designers, constructors, maintainers, safety analysts, managers, etc., and the role they have in the safety of the plants. In the same way one should not only consider a single person in a specific position, but rather his/her complete social environment. This means that the scope of the modeling should be enlarged to the whale organizations responsible for design, construction, and operation of the plants [21].

The establishment of an organization is necessary when a task grows too large and complicated for a single individual to carry out. The task is then divided into subtasks given to different individuals. The requirements of the whole task are handled by introducing a coordination function among the subtasks. An important concept is the goal of the organization which is broken down into sub-goals embodying the intentional structure built in on each hierarchical level of the organization. The goal is usually formulated in general terms on the higher levels and more concretely on the lower levels of the organization. The goals can be described with a system, where means and ends alternate on different levels in the organization [22].

The command and decision making structures are important for the execution of the tasks of an organization. The structures are assigning the responsibilities among different members of the organization. The organization is usually defined formally, employing both organizational charts and written job descriptions. In spite of the formal descriptions, it is not always sure that the tasks are handled according to these rules, and one may here speak of an informal organization which is different from the formal organization. A large difference between the formal and the informal organizations can increase the danger of misunderstandings in how specific tasks should be handled.

In the study, of industrial safety it is especially important to be able to model teamwork because most of the work in the industry is based on teams with cooperation between different members having different skills. A description of teamwork will involve concepts like responsibilities, respect, and power. Leadership is also important, when the functioning of a team or an organization is considered. A leader should be able to introduce enthusiasm to the other members of the organization and to make their efforts in line with the objectives of the organization. A successful organization will attract skilled individuals which means that a successful organization will tend to be even more successful.

The task execution in an organization relies on a continuous exchange of information. The information system can be visualized as a network of nodes and branches, where messages are routed from information sources to the users of the information [23]. Deficiencies in the information systems can cause important messages to be delayed or to be erroneously routed. The communication between members in an organization will always be crucial for its performance because the division of the task into different subtask of different individual will require a coordination and message transfer between individuals responsible for interconnected subtasks. It is also important to communicate the organizational goals between the organizational units.

The incentive system provides the means for the control of individuals in the organization, where rewards and punishment will change the subjective utility functions of the members of the organization to be in line with the goals of the organization. When there are unresolved goal conflicts between the different members of the organization, there is always the possibility that intentional actions may introduce serious consequences.

An organization can be considered to have a memory in the written and unwritten rules of work practices. Organizations are also using models of the systems they are supposed to control. Some models are embodied in the organizational structure and other in the work practices utilized. The organization can sometimes be the subject of a very rapid process of change and in other cases the organizational memory may be that rigid that no change seems possible. An organization is always depending on the individual features of its members. Organizations have a similar kind of self-reference as individuals, where the image an organization has created of itself will influence its later behavior. This self-reference can also be seen in the commitment of the members to the organizational goals, which is a crucial aspect in ensuring the efficiency of any organization.

The modeling of organizations for the purpose of understanding human errors is still in its infancy. The interactions between members in a small group such as a shift team have not yet attracted enough attention. Still it is known that different shift teams may have very large differences in their strategies for operating a process [24]. Considering the framework of design, operational and licensing practices, obviously there are many different factors influencing how things are handled. Besides these already identified mechanisms of influence, there are many other important factors influencing the performance of an organization in the control of complex industrial processes.

7. UNSTRUCTURED DECISION MAKING SITUATIONS

Most of the modeling efforts in the study of human decision and choice have been directed towards well-structured decision making situations. Apparently an understanding has to emerge from simple cases to more complicated, but real life decision making often has a flavor that simple-models cannot describe. The concept of unstructured decision making situations is making a distinction between situations which are fairly well understood and those that are not.

In building an understanding of the behavior of a decision maker, it is necessary to build an understanding of the decision making situation itself. A decision error actually implies the existence of a correct decision which can be assured only in well structured decision making situations. For many real world decisions it is only possible afterwards to tell the correctness of a decision.

Much of our understanding of human decision making relies on the concept of rationality, which has been discussed extensively' in management science literature. Rationality is relying on a subjective utility function which gives a definition of superiority of a specific choice as- compared to a set of other choices. Rationality of individuals is seen in their efforts of optimizing their own subjective utility functions. Experiments have shown that the actual utility functions used tend to be much more complicated than usually thought.

A decision making situation can formally be seen as an optimization problem combining the following three parts:

- an utility function,
- a set of feasible actions, and
- a system model.

The utility function, in which the value system of the decision maker is embodied, establishes an order relation between different outcomes. The set of feasible actions gives the different opportunities the decision maker has to his/her disposal. The system model connects the actions to the outcomes and by that to the utility function. Real decision makers seldom formalize their decisions into such an optimization problem. Instead they are to a large extent using experience and intuition to select feasible options and to evaluate their relative merits.

This simple model of a decision situation provides several extensions towards more realistic situations. Several interacting decision makers with partly or completely competing objectives provide important extensions treated in the theory of games. A single valued utility function is not enough, where a compromise between multiple incomparable values has to be found. A straightforward generalization of the simple decision making problem is to consider stochastic systems instead of deterministic. Additional generalizations are obtained when there are actions making it possible to influence the utility function, the set of feasible actions, or the system model.

A decision situation can be considered a simple situation of choice when the difference in utilities between different action alternatives is small. A typical example is the selection of, a dish from a menu in a restaurant. Decision situations with a higher stake involved are typically given more resources in terms of efforts spent in optimizing the decision.

One difficulty associated with the real world decision making problems is to make a proper consideration of the time span of the optimization. A long span of the optimization is not always in the interest of a decision maker because the optimal solution can tend to give the benefits very late. A short span of the optimization can also be counterproductive because there are cases where an early investment in obtaining a favorable situation will pay off later. The use of discounted utilities can to some extent solve this problem but will, on the other hand, make the problems more difficult to solve.

In spite of the existence of well-structured decision making situations, there are examples where even simple problems show astounding properties. Non-linear differential equations are exhibiting chaos which makes their responses unpredictable. There are also examples of simple differential equations, which can go through a rapid unexpected change (catastrophe) if their state is taken through the existing folding of the state space. There are also simple games (e.g., prisoners dilemma and free rider) which have not yet been analyzed to the necessary depth to provide a full understanding of their inherent dynamics in an iterated play [25].

8. DECISION SUPPORT SYSTEMS

The fording that humans have difficulties in performing optimally in certain decision making tasks has led to the introduction of different decision support systems. The support systems can be aimed at different stages in the decision making situation, such as the detection of the need for a decision (alarm function), the search for the causes of the process upset (diagnosing function), and the evaluation and execution of decision alternatives (execution function). One approach in the design of decision support systems is to consider classes of typical decision errors and to suggest specific support functions, by which these decision errors can be avoided. This bottom up approach has the danger of building up poorly structured systems, but if it is combined with a top down consideration of the requirements it can be a viable approach.

Decision support systems rely on a task division between the operators and the automation. The bearing design principle is to assign the tasks so that the abilities of the human can be utilized in the best possible way. There have been suggestions that the decision making should be automated as far as possible. However, this is not the correct way of improving decision making quality for unstructured decision making situations. There are however tasks where the human capacity limitations, e.g., short time memory requirements, require extensive calculation, high reliability, and accuracy, what makes automation necessary. Tasks which are automated are by definition well structured because otherwise it would not have been possible to formulate them as unambiguous algorithms.

The design of an operator support system should always be based on a clear structure of the different functions included [26]. Many good principles for the design of control rooms and decision support systems have been developed. The principles ensure a prototype applicability of the systems which is necessary in avoiding the frustration of adapting to inconsistencies in the systems before the users can gain any benefit. It is also important that expectations of the operators are reflected in the design of the support system to make it easy for him/her to find and use different functions. The support system will to some extent also influence the task and the organizational structures at the plant.

One of the problems with present solutions of giving the operators support in the control rooms is associated with the handling of alarms. The present approach, where each process variable has a defined alarm limit and an associated alarm in the control room leads to a situation where also small process upsets can trigger an avalanche of new alarms. The operators have then large difficulties in separating relevant from irrelevant information. The utilization of intelligent alarm systems, where irrelevant information is suppressed, is the obvious solution of this problem [27].

The handling of the complexity of the industrial plant is another important task of the support system. The complexity is due to many interconnected systems, subsystems and components. The complexity is also increased by the large number of different physical phenomena, which are utilized in different parts of the plant. The automation is also increasing the complexity of the plants by adding another level of interconnections between the different parts of the process. The support in handling the complexity can be built as an intelligent interface which has many paths of association between different pieces of information.

There have been arguments on the advisability to let the support system give recommendations to the operator. The arguments are to some extent reflecting the role of the operators in the control room and to some extent the consideration of structured and unstructured decision making situations. It is not advisable to give the operators recommendations in unstructured decision making situations, because there is no assurance that the designed algorithms will be efficient. On the other hand it is important to note that an unstructured decision making situation may change into a situation where clear and simple algorithms can be applied. There will also be the problem of how responsibility is shared between the designer and the operator in the case the system gives an erroneous advice.

Artificial intelligence has been seen as a panacea to the problems of supporting human decision making. In spite of the potential of the technology, it is important to note that the methods still require the formalization of the problem to a degree that seems impossible for unstructured decision making situations. The suggestion of bringing in expert systems in the control rooms of the industrial plants also contains a danger of a too large reliance on the automated decision making. The use of expert systems for potentially dangerous processes will also bring forward the need for validating the correctness of the advice they are giving.

In spite of the limitations of artificial intelligence technology in providing a base for building operator support systems, obviously there are potentials for many improvements in present systems. Different operator support systems have been proposed- and the concept of safety critical functions have now been widely adopted [28]. Efficient hardware and' software have the potentials of bringing down the development costs of the support systems. Automated reasoning can have an impact on the quality of the new systems [29]. Before the new methods can have their' full' impact on the operation of the complex industrial plant there is still a large amount of work to be done in which the decision making situations should be structured and formalized. This will imply the development of qualitative modeling methods and better systems for handling reasoning about plant concepts and relations.

9. FUTURE CHALLENGES

The human part of the socio-technical system is very complicated and still poorly understood: To improve the safety of the industrial installations it is necessary to arrive at a better understanding of how different contributors are influencing the possibility of human errors. To improve the safety of industrial installations, there is a need for models by which it is possible to predict the' performance of the complete socio-technical systems and to use these predictions to optimize the design' of the systems.

Efforts in human-machine research should also aim at a systematization of existing knowledge to make it more easily available in guiding system design. In building better models of the industrial systems it is also necessary to understand the shortcomings of different modeling approaches. Especially for the modeling of socio-technical systems there is a need for merging quantitative and qualitative modeling approaches.

Models, analogies, and metaphors that humans are using in unstructured decision making situations are actually parts of an understanding of the world. Better insights in how these mechanisms are functioning would probably provide the guidance also for the' design of better decision support systems [30].

Handling the complexity of industrial installations during design, construction, and operation is necessary in ensuring the safety of the installation. Proper ways of structuring the information connected to the plant, the control task, and the operators have to be found. This implies again that a better understanding of the cognitive functions of the operator should be available.

Modeling human cognition and understanding is one of the challenges for systems analysis in the years to come. This work cannot be done without combining very many different skills into a coordinated multi-disciplinary effort.

10. References

[1] Allen R.W. and McRuer D., 1979. "The Man-Machine Control Interface Pursuit Control." *Automatica*, 15, 683-686.

[2] Bibby K.S., Margulies F., Rijnsdorp J.E., Withers R.M.J., and Makarow I.M., 1975. "Man's Role in Control Systems." IFAC 6th Triennial World Congress, Boston/Cambridge, Mass.,: USA, 24-30.

[3] Seminara J.L., Gonzalez W.R., and Parsons S.O., 1976. "Human Factors Review of Nuclear Power Plant Control Room Design. EPRI NP-309, Electric Power Research Institute, Palo Alto, CA.
[4] Palmgren A., 1988. "Man-Machine Systems and Plant Performance. IFAC/IFIP/IEA/IFORS Conference on Man-Machine Systems, Oulu, Finland.
[5] Perrow C., 1984. *Normal Accidents; Living with High Risk Technologies*. Basic Books, New York.
[6] Wahlström B. (1994). Models, Modelling, and Modellers; An Application to Risk Analysis. *European Journal of Operational Research*, Vol.75, Issue 2.
[7] Wahlström B., Heinonen R., Ranta J., and Haarla J., 1985. The Design Process and the Use of Computerized Tools in Control Room' Design. Nordic Liaison Committee for Atomic Energy, Stockholm, Sweden. NKA/LIT85/4.
[8] Wahlström B., 1992 "Avoiding Technological Risks; The Dilemma of Complexity." *Technological Forecasting and Social Change*, 42/3; 351-365.
[9] Bainbridge L., 1983. "Ironies of Automation." *Automatica*, 19/6, 775-779.
[10] Wahlström B., Laakso K., and Lehtinen E., 1989. "Feedback of Experience for Avoiding a Low Probability Disaster." In *Feedback of Operational Safety Experience from Nuclear Power Plants,* International Atomic Energy Agency, Vienna.
[11] IAEA, 1991. Safety Culture. International Atomic Energy Agency, Safety Series, No.75-INSAG-4, Vienna.
[12] Sheridan T., 1975. Considerations in Modeling the Human Supervisory Controller. IFAC 6th Triennial World Congress, Boston/Cambridge, Mass., USA, 24-30.
[13] Rasmussen J., 1976. "Outlines of a Hybrid Model of the Process Plant Operator." In *Monitoring Behavior and Supervisory Control*, Sheridan and Johannesen (eds.), Plenum Press.
[14] Rasmussen J., 1983. "Skills, Rules and Knowledge; Signals, Signs and Symbols, and other Distinctions in Human Performance Models. *IEEE Transactions on Systems, Man, and Cybernetics*, 13, 257-266.
[15] Rasmussen J., 1979. On the Structure of Knowledge - Morphology of Mental Models in Man-Machine System Context. Risø-M 2192, Risø National Laboratory, Roskilde, Denmark.
[16] Rasmussen J. and Lind M., 1979. Coping with Complexity. Risø-M 2293, Risø National Laboratory, Roskilde, Denmark, 1979.
[17] IAEA, 1989. Models and Data Requirements for Human Reliability Analysis. International Atomic Energy Agency, IAEA-TECDOC-499, Vienna.
[18] Linnerooth-Bayer J. and Wahlström B., 1991. Applications of Probabilistic Risk Assessments: The Selection of Appropriate Tools. *Risk Analysis*, 11/2, 239-248.
[19] Norman D.A., 1981. "Categorization of Action Slips." *Psychological Review*, 88, 1-15.
[20] Rasmussen J., Pedersen O., Mancini G., Camino A., Griffon M., and Gagnolet P., 1981. Classification System for Reporting Events Involving Human Malfunction. Risø National Laboratory, Report M-2240, Roskilde, Denmark.

[21] Wahlström B. and Swaton E., 1991. Influence of Organization and Management on Industrial Safety. In *The Influence of Organization and Management on the Safety of NPPs and other Complex Industrial Systems*, Swaton E. and Wahlström B. (eds.), International Institute for Applied Systems Analysis, WP-91-28, Laxenburg, Austria.
[22] Elrod E. and Hubbard C.L., 1979. Applying Means - Ends Decision Trees. , *Business*, Jan.-Feb., 17-25.
[23] Wahlström B., 1989. On the Use of Models for Designing Communication Systems for Accident Management. Commission of European Communities, Varese.
[24] Norros L. and Sammatti P., 1986. Nuclear Power Plant Operator Errors During Simulator Training. VTT Research Reports 446, Technical Research Centre of Finland.
[25] Axelrod R., 1984. *The Evolution of Cooperation*. Basic Books, New York.
[26] Wahlström B., 1988. On the Design of Decision Support Systems. IAEA Technical Committee Meeting on "User Requirements for Decision, Support Systems," Vienna.
[27] Rinttilä E. and Wahlström B., 1986. Handling and Presentation of Alarms During Nuclear Plant Operation. *Nuclear Safety*, 27/3, 343-351.
[28] Wahlström B., Smidt-Olsen H., Rinttilä E., and Meijer C., 1983. "Experimental Validation of an Operator Support System Using a Training Simulator." IAEA Symposium on Operational Safety of Nuclear Power, Marseilles.
[29] Välisuo H., 1993. Model-Based Reasoning and the Control of Process Plants. HWR-348, OECD Halden Reactor Project.
[30] Wahlström B., 1987. "On the Use of Models in Human Decision Making. In *Tasks, Errors and Mental Models*, B. Andersen, Olsen S.-E., and Goodstein L. (eds.), Taylor and Francis, Ltd., London, 160-170.