THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

A Conceptual Model for Analysis of Automation Usability Problems in Control Room Settings

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Abstract

The focus of this licentiate thesis lies on the problems that can emerge when humans and advanced control systems work together in control room environments. In the nuclear domain, automation is used extensively and it is important to maintain safe and efficient operations. Therefore, problems related to operator-control system interaction is a critical field.

In the thesis, these interaction problems are argued to be closely related to usability issues. Therefore a distinction was made between problems related to the applied levels of automation and problems related to usability. The latter have been defined as automation usability problems.

The first aim of the thesis was to propose a conceptual model that can capture aspects of human-machine interaction that are relevant for analysing automation usability problems. The second aim was to use the conceptual model for analysis of automation usability related problems and explain the emergence of different types of problems in a single framework.

By compiling the means-ends hierarchy, the perception-action cycle, control loop, performance influencing factors, levels of automation and mental models into a single framework, a conceptual model that is suitable for explaining automation usability problems has been proposed. The conceptual model was tested in analysis of the out-of-the-loop, loss of skills and trust problems, by using an analytical approach. The conceptual model was also used for analysing the out-of-the-loop and loss of skills problem by utilizing empirical results from a field study performed in the nuclear power domain with a turbine automation interface as an example.

The proposed conceptual model is intended to be used by human factors engineers working in industry. The industrial application is important to contribute to the design of safe and efficient human-machine systems. The conceptual model however needs further development before it is fully complete for industrial use. In further work, two tentative procedures for model use are suggested; a procedure for analysis of existing human-machine systems, and a for aiding the design of new human-machine systems.

Keywords: Human-machine systems, levels of automation, control rooms, cognitive systems engineering, nuclear power, usability problems

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List of publications

This thesis is a monograph that builds on the work presented in the following papers and reports. The appended papers have contributed to the results presented in the thesis. The additional publications present the research base on which the author has drawn his conclusions.

Appended papers

Paper I Andersson, J. (2010) *Using AcciMaps to describe the emergence of critical work situations – A systemic approach to analyse automation,* In D. de Waard, Axelsson, A., Berglund, M., Peters, B. and Weikert, C. (Ed.), Human Factors: A system view of human, technology and organisation, Maastricht, the Netherlands: Shaker Publishing.

Distribution of work: Single author.

Content: The paper describes how factors from four different organisational level contribute to the out-of-the-loop-problem during turbine operation in a nuclear power plant control room. This is illustrated by using an AcciMap representation.

Paper II Andersson, J. & Osvalder, A-L. (2009) *Levels of Automation and User Control,* In VTT Symposium (Valtion Teknillinen Tutkimuskeskus) 258, 107-110.

Distribution of work: The first author performed the field study presented in the paper and wrote the main part of the paper.

Content: The paper describes an empirical field study performed in a nuclear power plant simulator control room and presents how the use of an automatic turbine system affects nuclear power plant turbine operators' ability to stay in control during different levels of automation.

Paper III Bligård, L-O. & Andersson, J. (2009) *Use errors and usability problems in relation to automation levels of medical devices,* In VTT Symposium (Valtion Teknillinen Tutkimuskeskus) 258, 111-114.

Distribution of work: The first author performed the two studies presented in the paper. The first and second author made the analysis and wrote the paper together.

Content: The paper is a reflection on levels of automation in medical devices and the role level of automation plays in usability. The comparison of two dialysis machines showed that there was a difference in usability problem types at different levels of automation. A conclusion was that the usability aspect becomes even more important as the level of automation increases.

Additional publications

Additional papers that have been published related to the area of human-machine systems in supervisory process control. In all these papers, the author of the thesis has made significant contributions.

Osvalder, A.-L., Bligård, L.-O., Andersson, J., & Thunberg, A. (2010). Framework to describe and categorize a complex human-machine system. In D. de Waard, Axelsson, A., Berglund, M., Peters, B. and Weikert, C. (Ed.), Human Factors: A system view of human, technology and organisation: Maastricht, the Netherlands: Shaker Publishing.

Bligård, L.O., Andersson, J., Thunberg, A., & Osvalder, A.L. (2010). Graphical visualization of process status for thermal power plants. In D. de Waard, Axelsson, A., Berglund, M., Peters, B. and Weikert, C. (Ed.), Human Factors: A system view of human, technology and organisation: Maastricht, the Netherlands: Shaker Publishing.

Bligård, L.-O., Andersson, J., Thunberg, A., & Osvalder, A.-L. (2008). MMI-design av systemlösningar i kontrollrum - Arbetsprocess för utformning utifrån ett människa-maskinperspektiv (Värmeforsk Report No. 1047). Stockholm.

Andersson, J., & Osvalder, A.-L. (2008). In Search for Common Ground - How An Automatic Turbine System Supports Operator Work, European Conference on Cognitive Ergonomics 2008, 16-19 Sep., Funchal, Portugal (Vol. 2008, pp. 73-74).

Andersson, J. (2008). Levels of Automation and User Control (Project Report No. NKS-179). Roskilde: Nordic nuclear safety research.

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APPENDED PAPERS

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1
Introduction

This chapter is the introduction to the licentiate thesis: A Conceptual Model for Analysis of Human-Automation Problems in Control Room Settings. The chapter presents the background to the work and the purpose and aim.

1.1 Background

Automation can be used in both simple and very complex artefacts to enhance human abilities. A shovel is used to make digging more effective and a hammer is used to perform the pushing of nails into a piece of timber more easily. When using simple artefacts such as shovels and hammers the control of how the action should be performed lies completely within the human's motor skills and understanding of how to reach the intended goal. For example, a carpenter sees a nail, decides to peg it, picks up the hammer and hits the nail until it is flush with the board.

As artefacts become more complex, parts of the control are gradually moved to the artefact and an intermediate control step arises as a result of the use of a control system with an interface. When a carpenter uses a nailer instead of a hammer, the initial steps of perception and decision are equal to using a hammer, but the nailer exerts the force (decided by the control system) necessary to push the nail into the board when the carpenter pulls the trigger (the control system interface).

The perception and decision functions can also be moved from the human to the machine by use of e.g. sensors and computer technology, which means that the artefact takes over a larger part of the control during the performance of a task. When moving more and more functions from the human to artefacts, the artefacts become more advanced. When advanced artefacts are aggregated into systems that each performs a function to reach an overall goal, the complexity is further increased and the artefacts become more independent. Human involvement is thereby reduced. The machines become autonomous[1].

The main motive to use systems of autonomous machines is to reduce cost and improve accuracy and effectiveness. To achieve this, a need for advanced control systems emerges. The utilization of advanced control systems increases across domains and has led to the possibility of gathering control in one location – the control room. This development has many advantages, but also some potential problems.

The focus of this licentiate thesis lies on the problems that emerge when humans and advanced control systems work together in a control room environment. The examples used in the thesis mainly come from the nuclear power domain since most of the empirical studies have been performed in nuclear power plants and simulators.

A nuclear power plant is a complex[2], tightly coupled and safety critical socio-technical system. Despite the simple principle of boiling water to create electricity, the technical system achieving this becomes very complex due to the number and tight coupling of the inherent objects. The tight coupling means that effects of incidents and failures can propagate and

[1] Machines rarely (if ever) become completely autonomous since they still are dependent on humans for e.g. maintenance, programming and supervision. 'Work does not disappear, it takes new forms' as Bainbridge (1983) puts it.

[2] Complex can be defined as something 'consisting of many different and connected parts' (*The Oxford Dictionary of English* (revised edition), Oxford University Press, 2005).

affect other parts of the system. Due to the high complexity, the propagation of failures can be difficult to predict. Technology that acts autonomously makes the task of understanding what is happening, or what has happened, even more difficult.

The problems associated with the use of advanced control systems have the potential to increase cost and worsen production efficiency and thereby reduce the utility of using automation. Since the use of advanced control systems increases in complex technical systems, the associated problems can also be expected to increase if they are not dealt with. In the nuclear power domain advanced control systems is also an integrated part of the power plant safety, which means that automation related problems also can have safety critical implications.

In this thesis, the term ‘automation’ refers to how different functions are placed on the human and/or the machine during the performance of a task, rather than the autonomous artefacts as such. The automatic artefacts are instead described as objects that together form a technical system. This system is in turn managed by the operator using a control system.

The problems due to automation are related to the new roles that are created for operators when their tasks are changed from manual to supervisory control. From having performed tasks by hand directly on the equipment, operators now monitor representations of equipment and actions are taken by the advanced control system on a computer screen. This change implies a shift from work taking place close to the actual process to work performed as control from a remote location. This shift requires a sufficient operator mental representation of the process to be controlled. The control system should aid the creation and maintenance of such representations, i.e. function as a basis for operator decisions. The requirements on a sufficient mental representation however depend upon the task to be performed. For example, effective problem solving activities require a much more developed mental representation of the technical systems’ structure, processes and functionality than a simple task does.

A large part of the problems that are experienced in relation to the use of advanced control systems, are due to the difficulties of forming and maintaining mental representations. The operator needs a model of how the automatic system acts, react and what it performs at a given time. While the operator acts remotely by using the control system, the design of control system interfaces becomes an important issue. Since this is the window, through which the operator can view the process. To tackle problems that include both human cognition and complex technical systems, to design solutions that are useful for future control room operations, is a considerable challenge. It requires a framework that takes both cognition and technology into account and aid the creation of new technical solutions.

Automation problems can be divided into problems regarding where to allocate functions and problems regarding control system interface design. The problems regarding control system interfaces are closely related to usability, as will be shown further on in the thesis. Therefore, the problems emerging when automatic control systems and human operators work together are termed ‘automation usability problems’. The different types of effects and problems that arise in connection to the use of control system interfaces are acknowledged to be tightly connected, and the problems also affect each other. For example, the out-of-the-loop problem causes loss of skills, which in turn worsen the out-of-the-loop problem. Few generic models have been found that can be applied to describe and explain all problems related to the use of automatic systems and control system interfaces. A useful tool to understand problems that emerge when control systems are introduced can be of help for engineers in the analysis and design stages of automatic system development. In this thesis, an attempt is made to provide such a model.

1.2 Purpose and Aim

The overall purpose of this thesis was to contribute to the design of safe and effective human-machine systems that also makes use of the full potential of technology. The specific purpose was to describe how automation usability problems emerge, and to suggest how a systemic description can be used for analysis of human-machine systems in nuclear power plant control rooms. The results should be useful for engineers working in industry.

The aims were:

- To **propose a conceptual model** that capture aspects of human-machine interaction that are relevant for analysing automation usability problems

- To **use the conceptual model for** analysis of automation usability related problems and explain the emergence of different types of problems in a single framework

2
Automation from a systems perspective

This chapter introduce the concept of automation. The chapter also defines how the concept of automation is used in the thesis and discusses what implications automation may have on human work. The chapter also introduces Cognitive Systems Engineering and other theoretical concepts that are used in the thesis.

2.1 What is automation

Humans continuously strive to facilitate work. The reasons may be to make more and new tasks possible, to increase efficiency because of economic motives, or because we as humans are said to be lazy by nature. An example of how artefacts aid human work can be of help to understand why the problems that are addressed in this thesis exist. The nail pegging carpenter introduced in the background (Chapter 1.1) can be used once again. A peg can be pushed into a board by hand – it is not an easy task – but can be managed if the carpenter is strong enough. Pegging nails by hand (literally) is however not very effective. By using a hammer to peg the nail the task performance is enhanced since it pegs the nail faster when the force exerted by the carpenter can be directed more effectively through the nail via the hammer's head. The artefact interface is here represented by the hammers handle, e.g. how well the carpenter can grip it and how well balanced the tool is. The hammer interface affects how fast and precise the task can be performed. With a nail gun, the task is further facilitated by letting the nail gun exert the force necessary. The carpenter uses the trigger to fire a nail into the board but s/he doesn't have to apply the force by hand. On the nail gun the interface is represented by the handle, trigger and force adjustment. When the force adjustment is introduced, a simple technical control system is also established. When pegging the nail by hand or with a hammer, the carpenter is his own control system – now control has been partially moved to the nail gun[3]. If the task is to be further facilitated, other functions such as detecting where the nail should be placed and deciding how many nails that are necessary to put into a board, have to be performed by the artefact. Now a robot is a suitable machine to deal with the task. The robot however needs to be given instructions to know how to perform the task accordingly. The instructions are given by programming the robot's control system.

Figure 1 Automation in carpentry

Traditionally, *automation* is defined as a machine that acts on its own using a control system[4]. A control system and its control loops are however present in the entire continuum illustrated in figure 1, regardless if it is situated in a biological creature such as a human or in an artefact. The distinction of automation as a purely technical concept is therefore unnecessarily discriminating when discussing human-machine systems. A more useful definition of automation in relation to human-machine systems would be for example; 'the use of artefacts

[3] A form of open loop control since the carpenter has to close the loop by adjusting the exerted force.
[4] "automation *noun*" *The Oxford Dictionary of English* (revised edition). Oxford University Press, 2005.

to make task performance more effective'. This definition presupposes the use of a control system, regardless of where it is placed and it also includes the whole level of automation continuum.

Frohm (2008) defined levels of automation as *'The allocation of physical and cognitive tasks between humans and technology, described as a continuum ranging between totally manual and totally automatic'*. The gradual shift of where the primary control loop is placed when performing a task is a way to describe how the *level of automation* may change. To the left in Figure 1, the control loop lies completely in the human, whereas to the right it is moved into the machine. In practice, a secondary control loop (the human) is often needed to manage and supervise the technology so that it performs the intended task correctly.

Here, the term automation refers to the definition stated above, rather than to autonomous artefacts as such. These are instead described as objects that together form a technical system which in turn is a part of a human-machine system. The technical system is managed by a control system, which is supervised by a human operator. When the term control system interface is used, it refers to the interface used by the operators working in the control room. In this context, an 'operator' is the person controlling the technical process. His or her work can take place both inside and outside of the control room. When work is being performed outside of the control room, the operator is referred to as a field operator. Figure 2 shows a schematic illustration of a human-machine system, which has been tailored by Osvalder et al. (2009) for process industry control room.

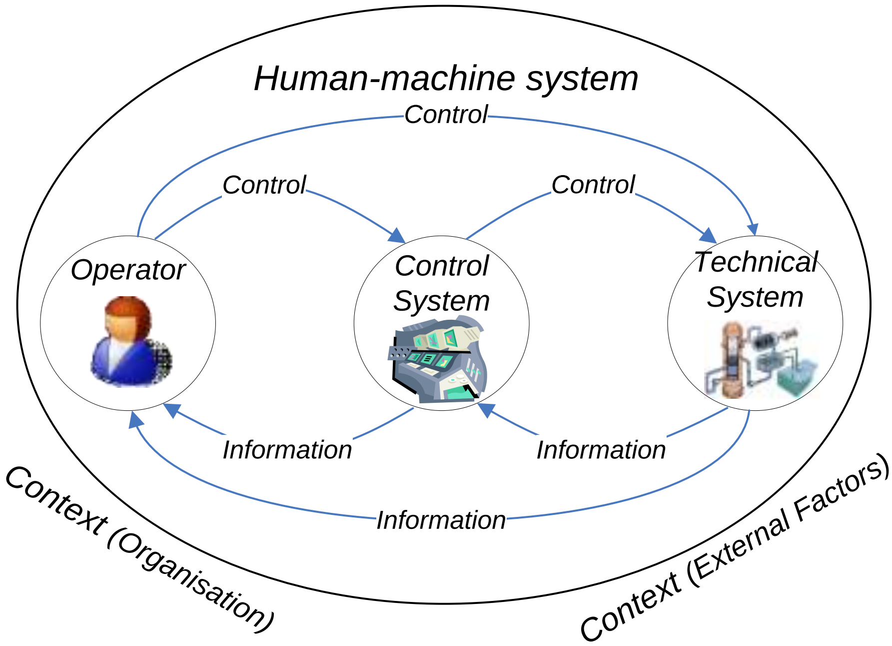

Figure 2 A human machine system (Osvalder et al., 2009)

Work can be described by the perception-action cycle (Neisser, 1976). As humans we perceive through our senses, analyse and make decisions via cognitive functions and act using our limbs. If a machine should function with reduced human involvement, similar functions are necessary. The machine needs to be able to sense, decide and act to reach autonomy. In the nail pegging example described before, the autonomous robot has to sense where it should place the nail, decide when and how many nails to peg and then perform the action. The robot also has to evaluate if the action was successful, and then decide whether to proceed to the next nail or remove the previous one.

The concept of control is important when trying to understand how human-machine systems work. This can be seen in the light of Neisser's perceptual cycle (Neisser, 1976) as a control loop. Humans act upon feedback from previous events and perceptions and are thereby always part of several control loops simultaneously. This is also the case for control room operators where several, often conflicting goals are dealt with at the same time (e.g. pushing production capacity and at the same time maintaining high safety standards). The control loops governing automatic processes are based on the same principles, which make control theory an important concept when considering joint human-control system activities.

Machines to varying extent can perform all the steps in the perception-action cycle. E.g., the perception of an important cue can either be made by the human sensory system or be measured by means of sensors (cameras, thermometers, accelerometers etc.). Humans can make analysis and decisions, but it can also be aided by computers. Actions can be performed manually, or by machines with little human intervention. Tasks can also be performed jointly by humans and machines together in a human-machine system. This way the *level of automation* (LoA) of the different steps in the perception-action cycle can vary across a continuum depending on how the human machine-system is designed (Parasuraman et al., 2000). An example of automation in perception is the use of sensors, which is a prerequisite for remote control. Figure 1 provides an example of the level of automation continuum in the action step and Sheridan and Verplank (1978) provide an early example of LoA in decision making in their work on undersea teleoperators.

An increase of the LoA also implies the introduction of a control system interface that the operator acts through and receives information from. Figure 2 shows a generic description of a human-machine system that incorporates an intermediate control system and its interface. This could be either a simple machine interface as described in the nailer example or a complex interface as in a process industry control room.

2.2 Cognitive Systems Engineering

The meaning of the three words in Cognitive Systems Engineering deserves an explanation. The word *cognitive* refers to the mental processes going on in the head of humans, but also to e.g. the decision making abilities of artefacts. Although humans put the functions there they are of a cognitive nature since perception, decision-making and choice of actions are inherent in such systems. The word *system* means 'a set of things or connected devices which operates together'[5]. This set typically consists of both humans and artefacts, i.e. a human-machine system that works together to achieve a specific goal. The complexity of such a system can vary greatly; from a nail pegging carpenter using a nailer, to the world's financial markets. A nuclear power plant control room lies somewhere in between these extremes. The term *engineering* has to do with problem solving through design. That is, to do something about problems in the world rather than just studying them. In the CSE context, problem solving is aided by providing insights and methodology on how to support the design of technology that supports human work.

[5] According to Cambridge Advanced Learner's Dictionary

One of the first scientific articles that referred to CSE as a field of research was written by Erik Hollnagel and David Woods (1983), and described the basic ideas of cognitive systems engineering. The article emphasizes the need for a change from the mechanistic view of the human-machine system to a view where the cognitive functions of the work system as a whole are acknowledged. Much of the ideas built on the work performed at the Danish National Laboratory at Risø around that time (Rasmussen, 1968, 1982; Rasmussen, 1983; Rasmussen & Jensen, 1974; Rasmussen & Lind, 1982). In CSE both technical systems and humans are described as being cognitive systems. Hollnagel and Woods (1983) further argued that to achieve work systems that performs adequately it is necessary both that the operator has a model of the system, but also that the system has an image of the operator and his/hers prerequisites. A goal of the CSE approach is to provide system designers with tools that facilitate the creation of work systems where human and technology have matching models of each other. This means that the operator needs a model of the process being controlled, but also that the technical system should have a model of the operator[6]. Thereby the opportunities for satisfactory system performance can be provided.

In recent CSE references (Hollnagel & Woods, 2005) the definition a cognitive system is 'a system that can modify its behaviour on the basis of experience so as to achieve anti-entropic ends'. The CSE agenda is stated as: 'how we can design joint cognitive systems so that they can effectively control the situations where they have to function'. This is not a new venture in human factors research, however, CSE asserts that a shift of paradigm is necessary, moving from a disintegrated view of humans and machines to a joint systems view. CSE stress the importance of system performance and how joint cognitive systems can stay in control in a dynamic context. This is made by using the work domain and its contextual factors on different levels of abstraction as a basis for analysis (Vicente, 1999). CSE contrast traditional human-machine interaction research by not emphasising the importance of the information process as a human cognitive structure and asserting that contextual factors are of greater importance than inherent mental functions to achieve adequate performance.

In sections 4.3.1 - 4.3.3, three parts from CSE that are of relevance to automation related problems in control rooms will be described; the abstraction-decomposition space, context and control and mental models. These constituents are later on used for model development and therefore an introduction is required. The main motive for using CSE as a framework is that it provides a functional structure that enables description of knowledge representations - that is the abstraction hierarchy. Context and control are of high relevance in the control room environment, especially since the work performed by the operator in a nuclear power plant is paced by the process rather than by the operator herself. Mental models are important since they represent the operator's knowledge and are the foundation upon which operative decisions are made.

2.2.1 The abstraction-decomposition space

The abstraction-decomposition space is a tool that can be used to represent a work domain (Bisantz & Vicente, 1994). By describing the work domain in terms of physical objects, functions and purposes, the resulting abstraction hierarchy is made independent of specific events (Bisantz & Vicente, 1994). Event independency is an important quality of a domain description since unexpected events are one of the greatest threats to safety in tightly coupled complex systems (Perrow, 1999). These events cannot be accounted for using task analysis

[6] Every artefact in some sense includes a model of its intended user, i.e. a hammer incorporates a model of the anatomy of a human hand. A vehicle safety system that sound when the driver is tired based on eye movements needs a model of the driver to respond adequately. Likewise, a control system in a nuclear power plant should be designed taking human cognitive abilities and limitations into respect; thereby a model of the operator is built in.

techniques since they are not yet thought of (or else they would not be unexpected when they occur). Performing a domain description by using task analysis techniques result in an event dependent domain description since tasks are tightly connected to what sequences to perform in specific situations. In this respect the abstraction hierarchy is preferable while it is clarifies the constraints that bound all possible actions, rather than describing the actions as such.

Normally, five levels of abstraction are used when constructing an abstraction-decomposition space. According to Naikar (Naikar et al., 2005) the following set of levels are useful; functional purposes, values and priority measures, purpose related functions, object related processes and physical objects. These instances are not described in detail here, however a pedagogical description can be found in Naikar (2005).

In exemplifying how means-ends relations can be used to describe a work domain, the nail pegging carpenter can once again be used as an example (

Figure 3). The purpose of the carpenter's activity is to fulfil customers' need for homes. This purpose can be fulfilled by building houses according to the plans specified by the customer. To achieve a readymade house several functions are necessary, e.g. masonry, plumbing and carpentry. Different processes, e.g. nailing, drilling and sawing, accomplish the carpentry function. The nailing process can be performed using a nailer or a hammer. This way the question 'Why?' is answered when moving upwards and the question 'How?' is answered when moving downwards in the means-ends hierarchy. The domain description does not include any specific task sequences that are necessary to build a house. Instead the functions required and how the processes and objects needed to achieve the goal of building a house are described.

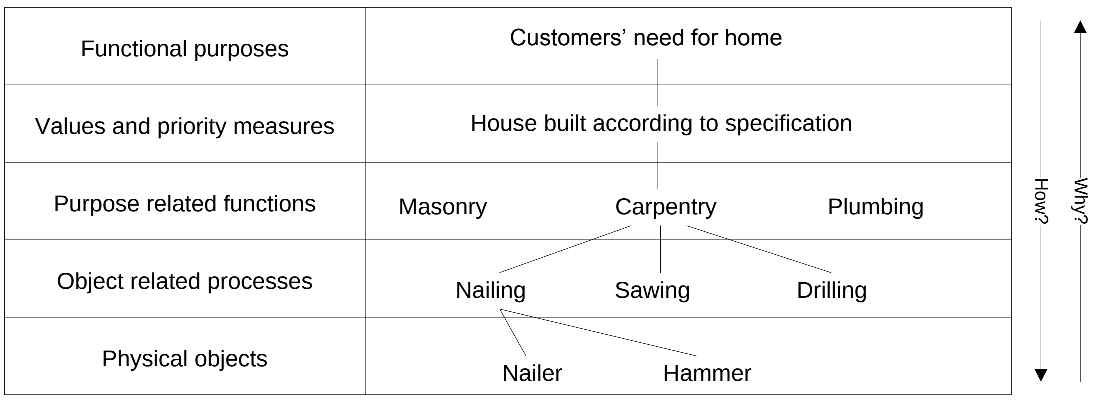

Figure 3 Means-ends relations in the house construction domain.

When the structural decomposition dimension is added, the domain constituents can be sorted according to their level of aggregation (Figure 4). In the example, the two top items are on the system level (home and house), the plumbing, masonry and carpentry functions are on the sub-system level. On the component level the objects used in the domain are found, e.g. hammer and nailer.

Abstraction \ Decomposition	System	Sub-system	Component
Functional purposes	Customers need for home		
Values and priority measures	House built according to specification		
Purpose related functions		Plumbing Carpentry Masonry	
Object related processes		Drilling Sawing Nailing	
Physical objects			Hammer Nailer

Figure 4 The abstraction-decomposition space

Following the same principle, a domain description can be made for a nuclear power plant. An example of this is presented in chapter 5 The Nuclear Power Domain. The abstraction-decomposition space becomes a simplification compared to reality but can be expanded to sufficient degree of detail depending on the purpose of the analysis.

The main feature of the abstraction-decomposition space is that it provides a structure to describe reality in both physical and abstract terms within the same framework. It can also be used to describe an operator's mental model of reality. This enable the mapping of cognitive work, which is an important aspect when addressing automation related problems.

2.2.2 Mental models

The concept of 'mental model' was introduced by Kenneth Craik (1943) and he described mental models as 'small scale models of reality' used to reason, anticipate and explain events. According to Wickens & Hollands (1999), successful control in the process industries is dependent on three components; (1) a clear understanding of the goals of production, (2) an accurate mental representation of the current state of the process and (3) an accurate mental model of the dynamics of the process. Because of the often slowly changing processes and therefore delayed feedback from actions, mental representations of the process are necessary to guide operator actions since they are forced to open loop control when handling slow processes (Wickens & Hollands, 1999).

Norman (1983) states that mental models are naturally evolving models meaning that a mental model change and develop due to interaction with for example, a technical system. A model is then formulated of that system. The model is not necessarily correct and seldom technically accurate, but it has to be functional to correspond with the target system behaviour. The model is continuously updated and modified as the user gain experience.

Preece (1994) presents the concept of mental models as consisting of *structural* and *functional* models. A structural model is used to describe the internal mechanics of a device in terms of its components. The structural models are often simplified models that help making predictions regarding the behaviour of a device with its internal structure as a basis (Preece, 1994). A functional model is a procedural model of how to perform a specific task. Functional models develop from previous knowledge of similar tasks or events. In new situations, functional models can facilitate the choice of how to act. Functional models can therefore be seen as task-action mapping models.

Although the importance of a match between the system to be controlled and the operators' understanding of how it works, it is important that the design of control system interfaces is not based upon the operators' mental models (Vicente, 1999). Instead, interface design should take its starting point in the physical world and take the constraints present in the work domain into consideration. When applying the 'cognitivist' approach (Vicente, 1999) to design by using the operator's mental model as a foundation for interface design, there is a risk of introducing a mapping between the physical system and the control system that is based on an incomplete or erroneous mental model. This can in turn lead to inadequate operator behaviour if it is used in control room operations.

In the cybernetic perspective of CSE, the human as a controller has to be at least as variable as the process or system that is controlled to be successful (Hollnagel, 1999). Conant and Ashby (1970) also stated that 'every good regulator of a system must be a model of that system'. In CSE this means that since humans can be seen as regulators in joint cognitive systems, the operator is a model of the controlled process and need at least as much variability as the process. By this follows that to predict the performance of a joint cognitive system the human operator as a regulator needs to be modelled, rather than modelling the mental model of the operator.

2.2.3 Context and control

To direct and manage the development of events and thereby stay in control, a nuclear power plant operator has to engage in closed- and open-loop control. Closed-loop control means that corrective actions are taken based on information from the feedback received from the control system as the process is undergoing. This means that the operator has to have a notion of the desirable state at a given time. The desired state (from mental model or procedure) is compared with the actual state and the action to be performed is chosen as to minimize the difference between these states. The feedback-evaluation-action (or perception-decision-action in Neisser's terms) cycle is continuous over time.

Open-loop control strategies are used for example when there is not enough time to wait for feedback or when feedback is extensively delayed. The operator then takes action based on a model (mental or simulation) of the process, which aids the prediction of how the process will answer to a specific action. For effective open-loop control it is then essential that the applied model is correct and that nothing that has not been accounted for in the model, happens after the action has been made. Or else the control action will not have the intended effect. In reality, the closed- and open-loop control strategies are however mixed. Every part of closed-loop control contains a little bit of open-loop control and vice versa (Hollnagel & Woods, 2005).

Control can also be exerted at different levels, i.e. at different levels of aggregation and abstraction (Rasmussen et al., 1994; Sheridan, 2006). An example from nuclear process control is how turbine automation can be controlled at object level as a sensor-actuator loop. This would represent a low level of control. Control can also be exerted on functional groups consisting of several objects that in aggregation fulfil a specific function, for example a number redundant pumps fulfilling a cooling function. On a higher level, control is applied by automatic sequences where functional groups and objects are activated upon orders given from the sequence program. The program also monitors itself and stops if all necessary conditions are not fulfilled.

The human involvement and role in control of automatic systems depends on the level of automation. In manual control the operator acts on the object or functional group level, hence performing control on a lower level of aggregation. When a high level of automation is used, all of the control levels mentioned above are active and the operator acts as a supervisor on a high level where system and sub-system functionality is monitored rather than individual objects. There is also an element of meta-cognition as the operator monitors her own performance and balance workload, which has as yet been given little consideration within the area of process control (Lau et al., 2009). With several continuously active control loops both within the technical system, within the human and between the human and the technology, the control loops are nested in the joint cognitive system. The main point here is that the control theoretical perspective is a useful concept when considering human-machine systems. Especially when analysing when and how control can be lost, which is highly undesirable in safety critical systems.

Modelling the loss of control

Hollnagel (Hollnagel, 1993) has suggested a model to describe how operators cope with their job in dynamic environments. COCOM has its origin in Neisser's perceptual cycle (Neisser, 1976) and describes how current understanding determines what actions are taken to reach a specific goal. The action in turn produces feedback that modifies the understanding (Figure 5). The model has been shown to be useful to model performance in a number of contexts and situations (Hollnagel, 2002).

A central concept in COCOM is time. According to Hollnagel and Woods (Hollnagel & Woods, 2005), time is central to stay in control and can thus be used to model control performance. The main components to model control are; time to evaluate, time to select action and time to perform an action. The full set of time components can be found in (Hollnagel & Woods, 2005).

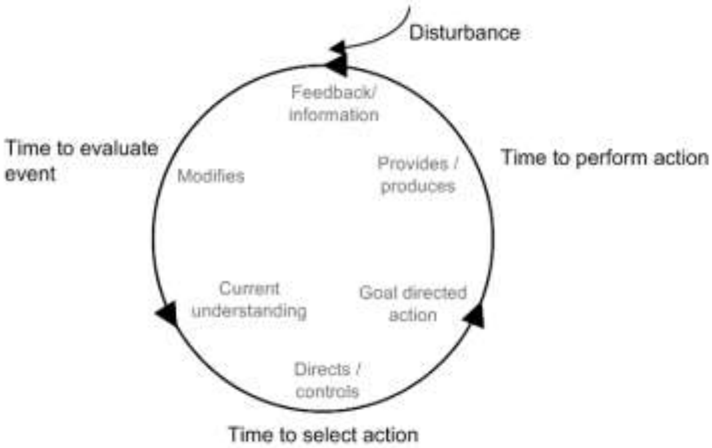

Figure 5 The Contextual Control Model (COCOM) adopted from (Hollnagel & Woods, 2005)

When the time needed to evaluate, select or perform an action becomes greater than the time available, control performance is affected. For example, if the operator does not have time to evaluate what has happened before he makes the next decision, the chance of making mistakes increase which gradually can lead to deteriorated control performance.

The COCOM describes the basic dynamics of control but is not able to account for how control takes place at different levels simultaneously during the performance of a task. For example, the carpenter pegs a nail by controlling his movements to hit the head of the nail with the hammer, but he also need to position the board for it to achieve its intended function in the wooden structure. At the same time, the carpenter has an image of the whole house in mind and controls the assembly of wooden structures to achieve the purpose for which the house is built. Similarly, when driving a car there are simultaneous loops to position the car on the road, watch out for other traffic and choosing the correct direction to reach the destination. The extended control model (ECOM) has been developed to provide the features for modelling of simultaneous control loops (Figure 6)(Hollnagel & Woods, 2005).

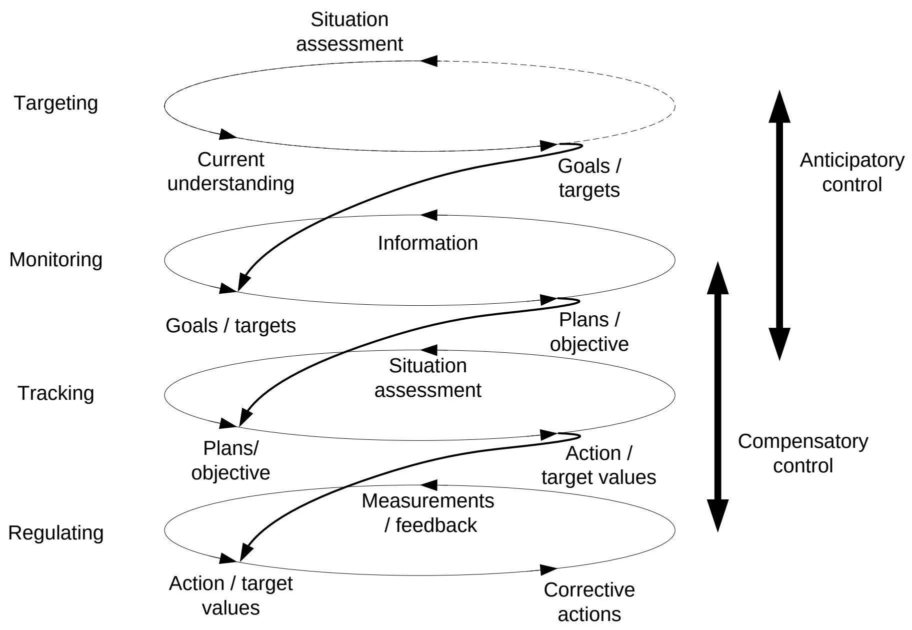

Figure 6 The Extended Control Model (ECOM) as described in (Hollnagel & Woods, 2005)

2.3 Performance Influencing Factors

PIFs can be divided into human-, task-, technical system, and environment factors (Kim & Jung, 2003). Human PIFs refer to the individual operator's abilities and delimitations, for example the operator's cognitive capacity. Task PIFs refer to the demands the task infer on the operator. Technical system PIFs refer to state of the technical system and process characteristics. The environmental PIFs relates to for example team and organisational aspects and physical working conditions.

2.4 The concept of usability

According to Grudin (1992), usefulness is a measure of how well a technical system can achieve a desired goal. Usefulness can then be divided into two aspects: utility and usability. Utility depends on whether the functionality of the technical system can perform what is required, while usability depends on how well the user can use that functionality. In the case of a drilling machine, utility refers to the drill's capacity to make holes, whereas usability describes how well the user can handle the drill while it bores holes.

In the example of the carpentry example used in the introduction, it is easy to employ Grudin's (1992) distinction between usability and utility. In monitoring of complex and safety critical processes, the control system interface needs to be both *useful* in the meaning that it provides necessary functionality for monitoring and control, and *usable* meaning that it present information in a way that is adapted to human abilities. For example, a hammer is useful in the meaning that it provides necessary functionality for effective nail pegging. To be usable, it also needs to be adapted to the user in terms of e.g. weight, size of handle and good grip. The hammer can be perfectly usable in an ergonomic sense, but still lack usefulness if it does not peg nails effectively. In comparison, a useful control system interface means that the information needs of the operator are satisfied and that the operator has sufficient means for control. For a control system to be usable it is necessary that the information is displayed in a way that facilitates perception and decision making. Without these qualities there is a risk for ineffective monitoring meaning that important information might be missed hence leading to the process not being controlled in an optimal way.

A further refinement of the concept of usability has been made by Jakob Nielsen (1993). Nielsen (1993) follows Grudin's (1992) distinction that functionality (utility) is not part of usability. Moreover, Nielsen maintains that usability has multiple components and is associated with five usability attributes:

- *Learnability:* The system should be easy to learn so that the user can rapidly start getting some work done with the system.
- *Efficiency:* The system should be efficient to use, so that once the user has learned the system, a high level of productivity is possible.
- *Memorability:* The system should be easy to remember, so that the casual user is able to return to the system after some period of not having used it, without having to learn everything all over again.
- *Errors:* The system should have a low user error rate, so that users make few errors during the use of the system, and so that if they do make errors they can easily recover from them. Further, catastrophic errors must not occur.
- *Satisfaction:* The system should be pleasant to use, so that users are subjectively satisfied when using it; they like it.

Nielsen (1993) describes a usability problem as any aspect of the design that is expected, or observed, to cause user problems with respect to some relevant usability measure (e.g. learnability, performance, error rate, subjective satisfaction) and that can be attributed to the design of the device. Thus, a usability problem in a system can have the result that the user does not attain a goal, that the use is ineffective and/or that the user becomes dissatisfied with the use. There is also an ISO definition of usability, but since the application of the usability concept to automation is better supported by Nielsens definition, that definition is used in the thesis.

Jordan (1998) also describes a set of ten principles that affect the usability of a product. These can be used as heuristics in the evaluation of user interface. Below follows a short description of each heuristic.

Consistency

Designing a task for consistency means that similar tasks should be performed in similar ways. This ensures that an operator can take experience from another task and use it when performing another task. Consistency also helps avoiding confusion and mistakes made due to using a sequence of actions in the wrong situation. For example, turning the volume up on a stereo is usually done by turning the volume knob clockwise. The opposite configuration would cause confusion. This heuristic is even more important within a technical system where similar controls are expected to be handled in the same way and give similar effect.

Compatibility

Compatibility means designing a product so its method of operation is compatible with users' expectations based on their knowledge of other types of products. For example, shifting gear in a car is made in a similar way in all cars with manual gearbox.

Consideration of user resources

Consideration of user resources means designing a product so that its method of operation takes into account the demands placed on the users' resources during interaction. For example, the design of a driver's seat and dashboard is adapted to the driver's need of directing attention in front of the car.

Feedback
The feedback heuristic means designing a product so that actions taken by the user are acknowledged and a meaningful indication is given about the result of the action. The feedback should be given as soon as possible while long feedback times make it difficult to know if the action has had its desired effect.

Error prevention and recovery
Error prevention and recovery means designing a product so that the likelihood of user error is minimised and so that if errors do occur they can be recovered from quickly and easily.

User control
User control means designing a product so that the extent to which the user has control over the actions taken by the product and the state the product is in is maximised. In the example of driving the introduction of the anti-lock braking system has enhanced the driver's control over the car.

Visual clarity
Visual clarity means designing a product so that information displayed can be read quickly and easily without causing confusion.

Prioritisation of functionality and information
Prioritisation of functionality and information means designing a product so that the most important functionality and information are easily accessible to the user.

Explicitness
Designing a product for explicitness means that cues are given so the product's functionality and method of operation are clear and without ambiguities.

3
Automation related problems

This chapter describe problems that can emerge due to use of automatic systems. The term 'automation usability problems' is introduced and examples of automation usability problems are presented as described in theory.

3.1 Automation usability problems

The effects of increased levels of automation (LoA) are multi-faceted. The purpose of automation is often to increase productivity and to maximise system performance. Therefore the effort to find the most suitable LoA is an important part of optimising over-all system efficiency (Frohm, 2008). The optimising effort has to be balanced and include humane considerations if the work of the operators left in the production system[7] is to remain meaningful. When increasing the LoA there is a risk that the jobs left will consist of either very easy tasks or the most difficult tasks (Bainbridge, 1983). The easy tasks are left since they are more expensive to automate compared to leaving them to a human operator (e.g. tasks that seldom occur). The most difficult tasks are often left to the operator, since they are too difficult or expensive to solve technically, for example tasks where the prerequisites for successful task completion is changed from time to time and therefore hard to foresee when programming the control system.

Due to an increase in LoA, the operator roles are also changed from active work to passive monitoring often performed from a remote control room. Since humans are poorly suited to perform passive and monotonous work (Bainbridge, 1983), the operators' vigilance and thereby monitoring performance may be reduced (Parasuraman, 1987). The operator's attention is however needed in case of a critical failure in the technical system. In an automatic system these failures seldom occur (i.e. if the system is well designed from a production efficiency point of view), causing the work situation to quickly change from serenity to extremely stressful. The description of work in highly automated systems as consisting of '99% boredom and 1% sheer terror' (Bibby et al., 1975) hardly seems desirable.

Another problem of increasing LoA is how automation that may be introduced to benefit safety instead is used to increase production, thereby diminishing the intended safety margins (Lee, 2006). This type of 'risk homeostasis' has been noted in several domains and is an effect that has to do with more than just the introduction of new technology (Rasmussen, 1997). Organisational pressures (often with economical background) that affect individual behaviour either by pushing the limits of the technology, or to reduce their own efforts, can have impact on system safety due to risk homeostasis. These examples of problems related to increasing LoA can be addressed by changing to a LoA that do not bring these side effects (Frohm, 2008). Often the change of LoA means use of intermediate LoA or letting the human operator decide how and when to use automation. Norman (1990) however argued that "the problem is not too much automation, it's the lack of feedback". This argument puts focus on the design of user interfaces through which most of the feedback is presented. Similar

[7] Production here also includes process industry applications, although the term is often associated with assembly line type of work.

arguments have also been put forward by other researchers in their efforts to determine how to achieve effective human-machine collaboration (Klein et al., 2005).

Norman's (1990) argument implies that there are other issues apart from the choice of level of automation. The lack of feedback that Norman refers to is not a lack of data per se. The number of sensors in process industry machinery today is larger than ever, and to simply present this data to control room operators will not make them perform their job better (Endsley et al., 2003). It can rather put them in a state of data overload where the task of distinguishing important information can become difficult due to the large amount of data in relation to the available attention resources (Woods et al., 2002). The control system designer therefore has an important role in providing means for effective information visualization that supports the operator in his or her work. This task is naturally connected to the use of automation but can be distinguished from the problems regarding the level of automation described above. The level of automation is independent of the control system interface design since the level of automation is decided on engineering considerations (Hollnagel, 1995), often based on an economical rationale. Regardless of what level of automation that is applied, the information from the technical system has to be appropriately presented – however the importance of an appropriate control system interface design increases with the level of automation if the operator is to be able to follow the technical process.

The large amounts of information and number of screen images that are necessary to control a complex industrial process (e.g. a nuclear power plant), challenge the human perceptual and decision making abilities. For the operator to make as much use of the available information as possible (and thereby controlling the process optimally as well as detecting and avoiding problems) the interface has to be conveyed in a way where it corresponds to and represents the physical constraints of the controlled process. It also needs to be coherent, meaning that the operator can understand what is presented (Bennet et al., 2006). The control system interface functions as a window through which the operator can view the controlled process and since the operators control the process from a remote location the control system interface becomes a vital source of information. Therefore, the quality of the interaction between the human operator and the control system is very important.

It can be argued that problems due to automation and problems regarding usability are intimately related when discussing control system interfaces. For example the out-of-the-loop problem (described further in section 3.2.2) concerns the difficulty for operators to detect problems in and automatic system and revert to manual control (Endsley & Kiris, 1995). This difficulty can be directly related to the interface heuristics of feedback, visual clarity and explicitness (Jordan, 1998). All of the automation related problems are however not related to usability, neither is all usability problems related to automation. The relation between automation and usability can be illustrated using a Venn diagram (Figure 7). The diagram show how automation related problems partly consist of problems that can be related to usability. An example of an automation problem that have nothing to do with usability is how to decide what level of automation to use to maximise work system efficiency and still maintain interesting jobs for the people who are left. Similarly, usability problems often concerns interface details that have little to do with automation, for example how drop down menus are designed. The main point here is that much of the usability related terminology and methodology is useful when discussing automation related problems.

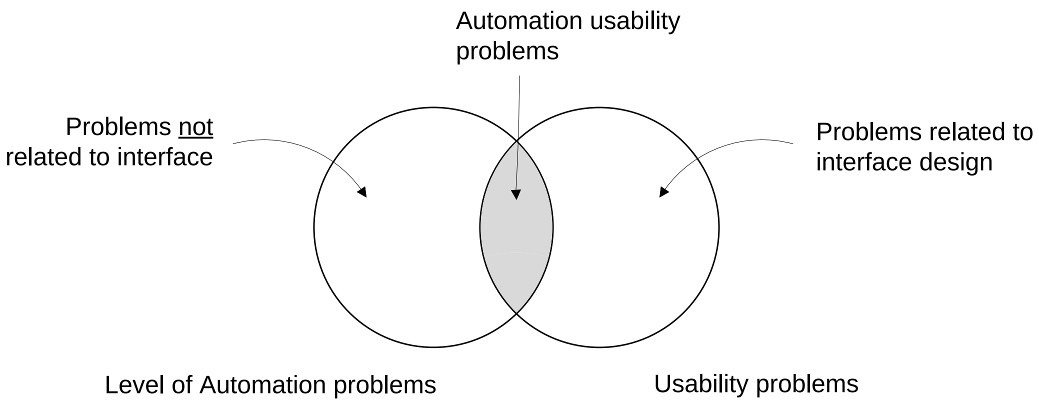

Figure 7 The relation between automation and usability

An aspect of the ‘automation usability problems’ - the grey area in the Venn diagram - is how knowledge is affected by the use of automation. Norman (2002) showed through some simple examples that knowledge can be distributed and placed both "in the head of the human" (or the operator) and "in the world" - e.g. built in to artefacts to assist the operator during use of the artefact. This implies that user interfaces can be seen as carriers of knowledge. The control room operator does not need to keep everything in his or her head, but can to some extent rely on the interface as representing part of the knowledge that is necessary to operate the plant.

To illustrate how knowledge is distributed between the world and the head a thought experiment can be useful; imagine a fully functional control system interface in a process industry. The operator can use the interface to adjust process values to optimise the production by clicking the objects on the screen. The only peculiarity with the interface is that the screen is completely blank - the objects and the functionality to control the plant are still there but nothing is shown on the screen. A (truly) minimalist design as imagined above would certainly have major impact on the operator's experience as a user of the control system and the ability to perform tasks. As a result, the knowledge of where objects are placed and how process equipment is connected needs to reside in the head of the operator if the control system is to be useable at all. Following the same line of argument then implies that a control system with good usability requires less knowledge for appropriate use, since the knowledge is placed "in the world" (i.e. in the control system interface) rather than in the head of the operator. In reality, the knowledge however resides both in the operator and in the system simultaneously, where more knowledge inherent in the control system would mean more support to the operator relieving her of cognitive effort.

The information and controls provided in the interface represents the intermediate ‘knowledge in the world’ that has to depict the physical process. It is equally important that the control system interface and the physical process correspond to each other as well as the operator’s representation of the physical process has to match reality. If the operator’s representation does not match reality, it can lead to deteriorated ability to maintain control of the process. The operator’s representation of how the system should be controlled in various states also has to match the designer’s intentions, this means that the designer of the control system has to foresee what information the operator might need (Rasmussen, 1986). Examples of the deteriorated ability to maintain control when using control systems are further described in the following section.

3.2 Examples of automation usability problems

This section introduces the potential problems that emerge when humans and control systems are to cooperate to achieve a common goal. The research regarding how automation affects work system performance, has primarily been performed in the aviation domain, but also in process control, shipping and medicine. The problems are described and examples are given on how they emerge and the possible consequences that may result.

3.2.1 Clumsy automation

Clumsy automation can be defined as poorly designed automation technology that makes easy tasks easier and hard tasks harder (Wiener, 1989).

Wiener (1989) found that automation caused pilot workload to increase rather than providing task support when workload reduction was needed the most. This happened since the automatic features were too difficult to use in situations that were already high in cognitive workload. The pilots then switched the flight management system off and reverted to a lower level of automation, this however means that all useful features of the flight management system also are lost (Billings, 1996). Bainbridge (1983) also stated that it is often the easy tasks that are automated while the difficult tasks are left to the operator to deal with. A reason for the difficult tasks being left is that the automation designer could not think of how to automate such complex tasks. The result may be that automation makes the operator’s job more difficult, rather than providing assistance. In usability terms, clumsy automation is an example of poor efficiency. The ‘productivity’ cannot reach a sufficiently high level when needed.

3.2.2 The out-of-the-loop problem

The out-of-the-loop performance problem has been defined as *‘automatic system operators’ diminished ability to detect system errors and subsequently perform tasks manually in the face of automation failures’* (Endsley & Kiris, 1995).

The emergence of the out-of-the-loop problem depends on a number of factors. Firstly, a high level of automation may reduce the feedback from the controlled process. Since control room operators are monitoring and controlling from a distance, the direct physical feedback is reduced compared with locally performed manual control. The available feedback is then reduced to the information presented through the control system interface and what is received through communication with field operators. Secondly, a high level of automation puts the operator in passive observation of the process rather than active control, which puts higher demands on operators to maintain their vigilance. Automatic control also means that operators have time to engage in other tasks than just monitoring the controlled process. This means that attention is directed elsewhere than the control system, which may make it difficult to follow how situations evolve.

Due to the reduced feedback, passive observation and directed attention, the out-of-the-loop problem also lead to reduced situation awareness (Endsley et al., 2003) meaning that the operator does not know what has happened in the past, has a poor understanding of what is happening at the moment and also will have difficulties in planning and deciding what to do next.

Early detection (before alarm) of deviation depends on knowledge of normal process behaviour, i.e. a mental model of the controlled process. This knowledge may diminish over time due to the reduced need for close monitoring of an automatic process and the diverted attention. The skills needed to take over the tasks performed by the control system are also likely to go unpractised when the control system functions as it should. This makes it difficult to detect deviations and resume manual control if the control system fails, thus leading to out-of-the-loop symptoms.

Operators can however very well be out-of-the-loop and still perform excellent in terms of production goals and low number of incidents. It is when the situation demands detection and action (often in critical states) that the deteriorated abilities become observable. Moreover, it is not until the problems are observed that they are possible to attribute to an appropriate cause (e.g. poorly presented feedback from the control system interface). As operators detect problems and search for solutions they work themselves back into the loop until the situation is solved (Rasmussen, 1986). In usability terms, out-of-the-loop can be directly linked to the interface heuristics of feedback, visual clarity and explicitness , and also to consideration of user resources.

3.2.3 Loss of skills

In the context of automation usability problems, loss of skills can be defined as the deterioration of manual and cognitive skills and knowledge due to the use of automatic control systems that reduce the possibility to practice manual tasks. Thereby, the control system interface has to provide additional support to enable the operator to remember and perform tasks despite the lack of manual practice.

Loss of skills and knowledge occurs as a result of operators not getting the chance of performing manually the tasks that have been automated. This leads to deterioration of the physical task performance skills. The operator's mental representation may also fade if it is not regularly used and maintained, thus loosing cognitive skills (Bainbridge, 1983).
It is worth noting that loss of skills and the out-of-the-loop problem are dependent of each other since loss of skills worsens the out-of-the-loop problem when understanding of the controlled process is reduced. Also, the out-of-the-loop problem may cause loss of skills over time as the operator is not engaged in active control (Lee, 2006).

The nature of the needed skills can also be changed when a control system is introduced as an intermediate between the operator and the technical system (Figure 2). An increased level of automation means that manual actions are replaced by monitoring tasks, which increases the cognitive demands imposed on the operator. There is also a concern that operators, who use an automatic control system from the beginning of their career, will never have the chance to acquire the skills and knowledge needed in case of automation failure where manual control becomes necessary. This highlights the importance of simulator training, where operators get the chance of hands on practice. In usability terms, loss of skills is related to memorability since if the interface helps the operator to remember (i.e. place 'knowledge in the world') how tasks sequences should be performed, the lost skills would not raise a problem.

3.2.4 Trust in automation

The concept of trust in automation is used to describe to what extent an operator relies on an automatic control system. Operators can rely on automation to different extent and reliance can vary over continuous grades rather than being a static binary state of either too much or too little reliance (Lee & See, 2004). However, the simplified binary view is often used to make the description of trust in automation easier.

Overreliance or complacency is created as operators form beliefs of the technical system as being more competent than it actually is (Lee, 2006). On the other hand, operators can also come to form a sceptical view of the technology and hence attribute too little competency to the technical system. This is referred to as distrust (Parasuraman & Riley, 1997).

Eutactic behaviour is a term that is used to describe when an operator has appropriate reliance that may be inconsistent with the expectations of designers and managers (Moray, 2003). The operator can perform supervisory control in a way that the sampling frequency when monitoring is consistent with the probability of failure. However, since failures in automatic systems occur seldom, the distance in time between each sample is long, thus leading to a risk of failures being missed although the operators perform statistically correct. The operator's behaviour is often based on the trade off between the benefit of having time to perform other tasks (and directing attention elsewhere) versus the value of detecting failures and deviations. Monitoring the control system closely may not be worth the effort since deviations happen very seldom, however the operator pose a risk of being blamed for inappropriate monitoring although having a statistically appropriate monitoring behaviour.

If operator trust does not match the automations capabilities, problems with misuse and disuse can occur (Parasuraman & Riley, 1997). If the operator does not trust the automation to perform what is needed in a sufficient manner, automation is likely to be abandoned and the advantages of the automatic system may be lost and economical benefits reduced. Complacency on the other hand, can cause the operator to fail in noticing when the automation does not perform as intended.

Operators can also have varying degrees of functional and temporal specificity in relation to trust (Lee & See, 2004). High functional specificity refers to how trust is attributed to a specific part or subsystem's capability, whereas low functional specificity may refer to the system as a whole. Temporal specificity describes how trust changes over time – for example how the operator manage to adjust trust if an automatic function fails repeatedly. Low temporal specificity is how the operator's calibration of trust lags behind and changes too slowly. High temporal specificity exists when the operator change his conception of trust in an optimal way, i.e. continuously reconsiders whether an automatic system performs reliably.

A number of factors affect operator reliance. Primarily, a high reliance is formed as a result of adequate automation performance. Operators will come to trust technology that seldom fails, and to be sceptical towards technology that often fails to perform as intended (Moray & Inagaki, 2000). Trust is also affected by for example, the operators self confidence, perceived risk, interface features, the automations reputation etc. (Lee & See, 2004). In summary, trust is a multi faceted aspect of human-machine interaction that may lead to a number of unwanted outcomes. In usability terms, trust relates to mainly to the heuristic of explicitness.

3.2.5 Automation induced errors

Automation induced errors refers to the types of errors occurring as a result of increasing the level of automation. A reason that often is used as a motivation to increase the level of automation is to reduce human error. However, new types of errors have been shown to occur as a result (Lee, 2006). Three examples of these errors are brittle failures, mode errors and configuration errors.

Brittle failures

Brittle failures refer to when automation cause a sudden degradation of human-machine system performance. This can happen if the control system compensate for automation failures which then may go unnoticed by the operator. When the control system no longer can accomplish the compensation due to system constraints, over-all performance may degrade suddenly. This contrast to the often graceful degradation in manual work, where performance degrades more slowly over time and thus can be easily detected. In usability terms, brittle failures relate to feedback and explicitness

Configuration errors

In advanced automated human-machine systems, the control system can be configured to handle tasks in a specified way. For example, in the maritime domain the navigation system can be directed to keep a specific route and warn the mariners if the ship comes too close to another vessel. If the wrong margins are unintentionally entered the ship can come too close to other traffic at sea, especially if the automatic navigation system is heavily relied upon. Thereby, a configuration error can jeopardise safety. The same thing is applicable in aviation where the flight management system can be accidently fed with the wrong data, which may surprise the pilot and compromise safety. In usability terms, configuration errors relates to feedback, errors and error recovery.

Mode awareness and automation surprises

Mode awareness is the ability of a supervisor to track and anticipate the behaviour of an automated system (Sarter, N. et al., 1997). This has similarities with the out-of-the-loop problem. Since automated human-machine systems have the ability to change their mode of operation based on environmental or contextual input from sensors and coupled systems, it can be difficult to track and understand the actions of a technical system that seemingly acts on its own. This behaviour may lead to 'automation surprises' that may compromise safety and operational performance.

For example, Sarter and Woods (Sarter, N. B. & Woods, 2000) showed how pilots of the advanced Airbus A-320 experienced surprises as the aircraft acted unexpectedly in various situations. Some of the findings could be related to the high autonomy but low observability of the flight computer's actions and intentions.

Another example was provided by Lützhöft and Dekker (2002) in their analysis of the grounding of the passenger ship Royal Majesty. In this example, the mariners were for several hours unaware of the GPS signal being lost and the ship was navigating in dead reckoning mode, leading to the grounding 10 miles east of Nantucket Island. The cause of the grounding can however not be attributed to the single cause of a lost GPS signal but, as Lützhöft and Dekker made clear, the path of events were dependent of contextual, organisational, team and individual as well as technical factors all contributing to an escalating situation. In usability terms, mode awareness and surprises are related to feedback and user control.

3.2.6 Problem interaction

The automation usability problems described above are tightly coupled and affect each other. This can cause vicious cycles of positive feedback where problems worsen each other (Lee, 2006). For example, clumsy automation can cause workload peaks that increase the possibility of mode- and configuration errors. Recovering from these errors may further increase workload. Another example is how inappropriate trust may worsen the out-of-the-loop problem that further deteriorates operator skills. Figure 8 give an indication of the coupling between the described problems.

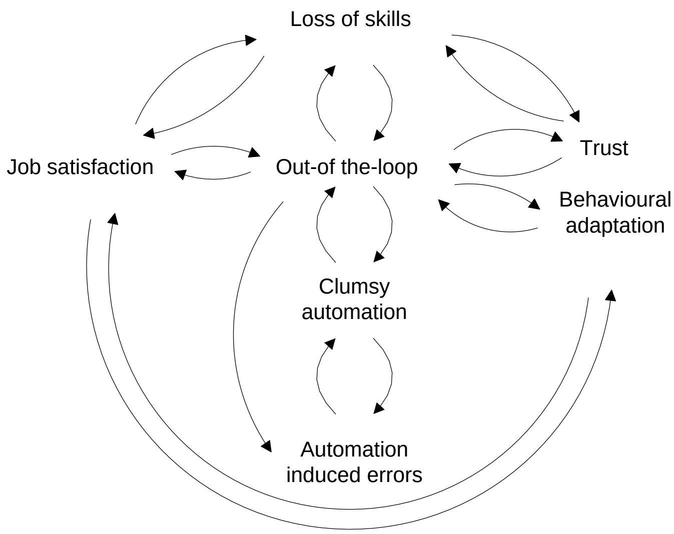

Figure 8 Human-automation problem interaction (adopted from (Lee, 2006))

Figure 8 reveal that the out-of-the-loop problem is a central issue when discussing automation related problems since it influence other problems and in turn is affected by them. The tight couplings between the problems motivate a systemic approach for analysis and design that take human, technical and contextual factors that affect performance into account.

4
A model to describe human-machine systems

This chapter describes a conceptual model to describe human-machine systems.

4.1 Why another model?

To guide how artefacts should be designed, a model can act as a mediating object to facilitate reasoning around a specific problem. If the model can account for real world problems, it is an indicator of that the model is able to catch the varying features of work. Automation usability problems have until now been described separately, with each problem described as a unique phenomenon that occurs during human-control system interaction. This model aims at finding a systemic way of describing and analysing these problems in a single hierarchical framework. However, the model components are not new. Each component has been thoroughly described in earlier research, but the assembled components however bring advantages that enable new possibilities to facilitate the analysis of human-machine system interaction. In Figure 9, the conceptual model is shown. In this chapter, the different parts of the model are explained and examples of how the model can be used are given, as an introduction to the descriptions of automation related problems presented in chapter 6.

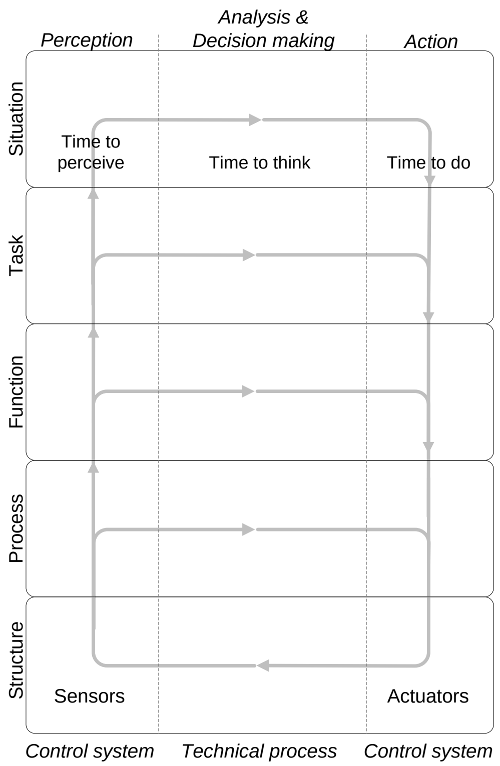

Figure 9 The conceptual model for description of a human-machine system

4.2 Model description

The model is constructed to represent a human-machine system, the human-machine system's activity and its context. To achieve this, the model includes five main theoretical components;

the means-ends hierarchy, the perception-action cycle, the control loop, performance influencing factors (PIF), and levels of automation (LoA). With the means-ends hierarchy as the foundational structure, the other constituents are incorporated. The means-ends hierarchy is used as a way to depict the work domain on different levels of abstraction. The perception-action cycle is used to describe how the joint system acts when it performs different tasks. This includes perception, analysis of information, decision-making and action. The control loop shows how control is exerted in the joint human-machine system. Performance influencing factors (PIF) are inherent in the *Situation* level to account for contextual influences. In a control theoretic perspective PIFs can be seen as disturbances that the system has to cope with. Including levels of automation allows analysis of how functions are allocated in the human-machine system and how this may affect system performance. The five theoretical components of the model are further presented in the theoretical frame of reference in chapter 3.

4.2.1 Describing the work domain

The first and fundamental part of the model is the means-ends hierarchy. Looking at the world by using different levels of abstraction is a useful way to understand complex systems, irrespective of domain. In this model, the CSE framework has been chosen to describe three of the five levels. Similar hierarchies have also been used in research on mental models (Hmelo-Silver & Pfeffer, 2004), where the domain was divided into structures, behaviours and functions.

In the model presented here, the hierarchy consists of five levels; *Structure*, *Process*, function, *Task* and *Situation*. The three lower levels is the task independent hierarchy that traditionally is used for domain descriptions within CSE (Rasmussen et al., 1994; Vicente, 1999). The two additional levels represent tasks and the work situation. The levels are related by the way they describe means and ends – that is, moving up in the hierarchy answers the question 'Why?' and moving down in the hierarchy answers the question 'How?' Figure 10 describes how the levels are related and how the level labels can be interpreted.

Starting from the bottom of the hierarchy Figure 10, the *Structure* represents the physical objects present in the work domain, and how these objects are connected physically to each other. For example, in a power plant, pipes that connect pumps and valves create the plant's physical structure. The *Process* level represents what happens when using the objects in the physical structure. In a power plant, the *Process* can be exemplified by the flow of water through pipes or the creation of steam by heating water. The *Function* level represents the reasons for why the process and structure exist. For example, the pumps, valves and pipes in a power plant are there to provide a cooling function to avoid excessive heat, which may damage the structure. The *Task* level represents what is being performed in the work domain to reach the intended goals. To perform tasks the operator uses the available functions to adjust or create a process by acting on the physical objects in the domain. The *Situation* level describes the overall work situation and contextual influences.

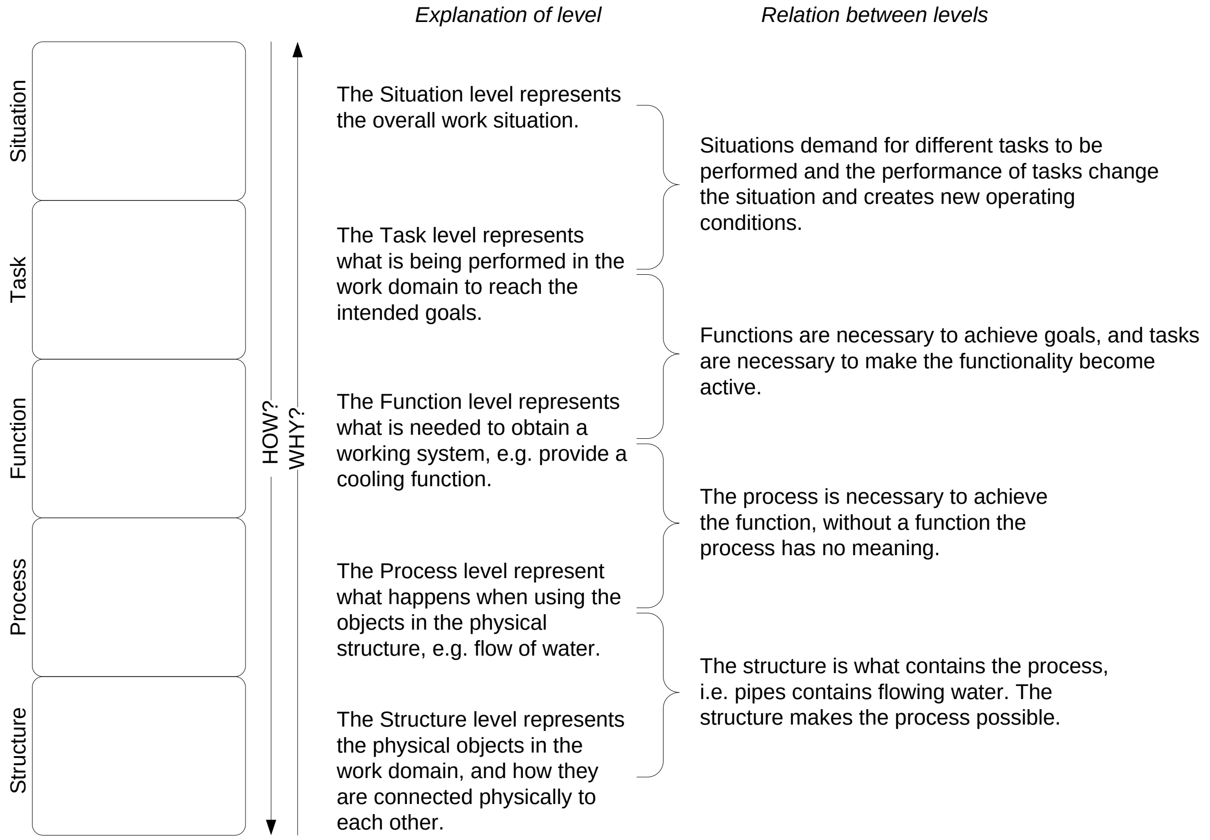

Figure 10 The model hierarchy

4.2.2 The control loop

The control loop represents how the human-machine system is controlled in the work domain. The loop has no given starting point or end point since the information flow between the physical structure and the different levels in the hierarchy takes place continuously.

The control loop is present in all levels of abstraction in the model (Figure 11). In a human-machine system, control actions are exerted to direct the objects in the technical system on the *Structure* level. At the same time, the process that is contained within the objects is regulated. Regulation also takes place on the *Function* level, but on a more abstract level. For example, in the *Process* level the flow of water is regulated but on the *Function* level cooling is regulated. On the *Task* level, the action sequences necessary to perform a task is controlled. The *Situation* level affects the levels below by influence of contextual factors. But the activities taking place on the *Structure*, *Process*, function, and task levels also influence the situation, thereby the situation changes and evolves dynamically.

The *Situation* level also contains the work organisation as a context. Operator actions affect their work situation and work organisation by the way they perform their job. The feedback from this level may however be delayed in time due to slow organisational processes. An example of how operators can improve their work situation are operators that collect experiences from daily operations, highlight operational problems, and forward this information to operational managers. The managers can in turn use the operators' feedback to improve operations, thus affecting the lower levels in the model. Figure 11 gives a clarification and exemplifies what each level in the model can contain.

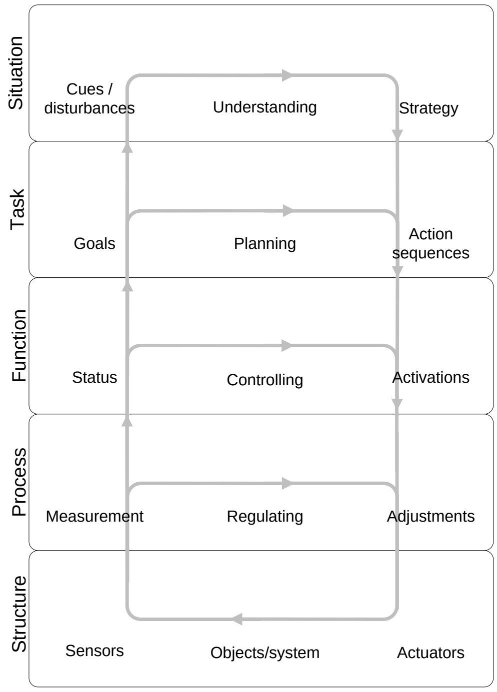

Figure 11 Control loops and content on different levels of abstraction

4.2.3 The perception-action cycle

In the model, the means-ends hierarchy is divided into three steps; perception, analysis & decision making, and action (Figure 12). Irrespective of it is a human or a machine that acts in the joint human-machine system; the steps of perception, analysis & decision making, and action are present. Perception represents how the human-machine system detects and takes in information. Analysis is related to how information is interpreted as a step prior to decision making. Decision making is the reasoning behind and the choice of what action to perform (or not to perform).

Perception in the human is achieved by input signals via our sensor organs, where vision is the primary sensing function. In the machine this is performed by mechanical sensors. The perceptual function is similar in both the human and the machine, but can have different sensitivity. In the analysis & decision making function, the capability of human decision making would correspond to artificial intelligence in the machine. Likewise, actions can be performed either manually by the operator or by a machine.

The perception, decision making and action steps are present in each level in the model. In the *Structure*, *Process* and *Function* levels, the perception step relates to how perception is achieved. On the *Task* level, it represents the information coming from the levels below. On the *Situation* level it mainly relates to time as a constraint. In the machine the time constraint is the sampling frequency, whereas in the human has to do with the limitations of our sensory systems.

The analysis & decision making step on the *Structure* level is governed by the laws of physics. On the *Process* level, the decision step represents the questions that need to be answered to regulate the process, e.g. is the process parameters within limits? On the *Function* level, the decision making step concerns for example whether the function (e.g. pumping) is available or not. On the *Task* level, it concerns how to determine whether the over-all goals are achieved. The *Situation* level relates to contextual influences that may affect decisions, for example available time, noisy environment or signals, or rapidly changing preconditions.

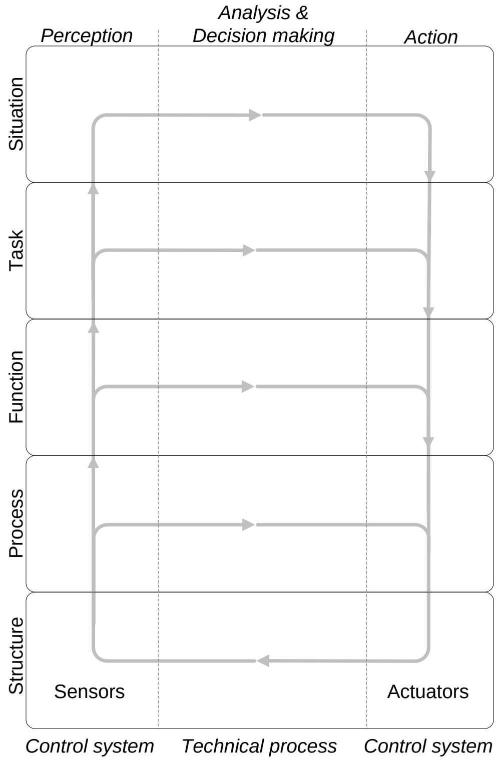

Figure 12 The perception-action cycle in each level

In the action step, the *Structure* level contains the actuators performing the physical actions. Either a machine part or a human hand can accomplish this. The *Process* and *Function* levels represent the signals or information necessary to direct the physical objects. The *Task* level represents the procedural steps necessary to achieve the intended goal, while the *Situation* level describes what affects actions in terms of contextual factors.

4.2.4 Performance influencing factors

Performance influencing factors (PIFs) are contextual factors that affect performance in a work setting. PIFs can be seen as disturbances acting on the different parts and levels of the control loop. For example, insufficient lighting can make perception more difficult and a tired operator is more prone to make poor decisions. Kim and Jung (2003) presented a compilation of PIFs from a number of sources to be used in human reliability analysis. The collection of PIFs from different methods can be of use also within the model framework presented here. The PIFs can guide reasoning of how different factors affect the *Task*, *Function*, *Process* and *Structure* levels of a human-machine system, with their inherent control loops.

One of the key PIFs is time (Figure 13). The time factor is ever present and can affect performance in several ways; too little time imposes problems of maintaining control since the time window for decisions and actions shrink. If a decision requires more time than the available time, it may result in a poor outcome – i.e. the operator ends up in a scrambled control mode (Hollnagel & Woods, 2005). In industrial processes, the pace of change of the process (its chemical reactions or physical sluggishness) sets the constraints of the time windows for decisions and actions. The same time constraints are valid for technical components since the sampling frequency of sensors, the bandwidth and processing capacity of computations, and the speed and precision of machine actions all are highly time dependent.

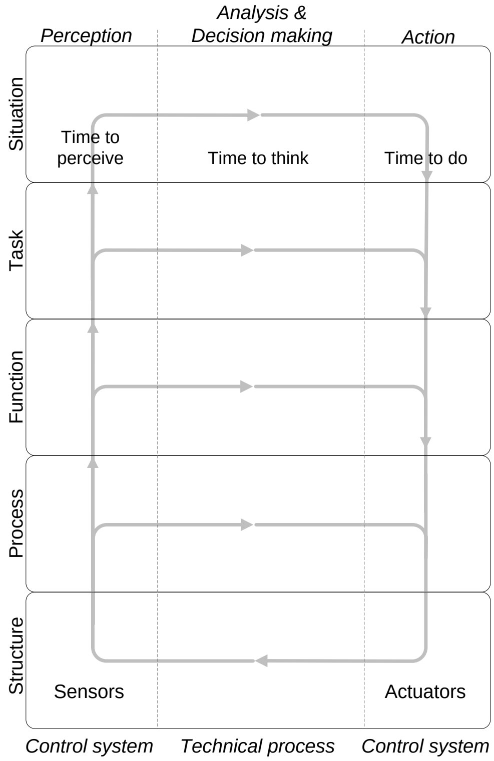

Figure 13 Time as a performance influencing factor in the *Situation* level

4.2.5 Levels of Automation

In the model, the Level of Automation (LoA) can be visualized by drawing a line of separation where control moves from the operator to the machine or vice versa (Figure 14). In this way the allocation of different functions can be illustrated.

For example, when pegging a nail with a hammer the carpenter himself is the actuator as he uses his hand and arm to swing the hammer and thereby controls the process (Figure 14a). He also embodies the carpentry function. The task of building a house is achieved when the carpenter's model of a house and what is built matches each other.

When a nailer is used, the LoA is changed (Figure 14b). The nailing process is partly performed by the machine (the carpenter still positions the nailer and pulls the trigger while the nailer exerts force on the nail), but the carpentry function is not incorporated in the nailer, it is still the carpenter that decides where to nail. Thus the LoA line is drawn at the *Process*/*Function* intersection.

If a carpentry robot is used, the LoA is increased another step (Figure 14c). Some tasks would probably still be located to carpenter, such as programming and make settings, i.e. decide what tasks the robot should perform. The LoA line is therefore partly drawn through the *Task* level. The actions of nailing would however be completely performed by the robot. The carpenter performs then supervisory control, by checking that the intended outcomes are achieved. The robot now inherits the carpentry function and the carpenter has received a new role in the human-machine carpentry system.

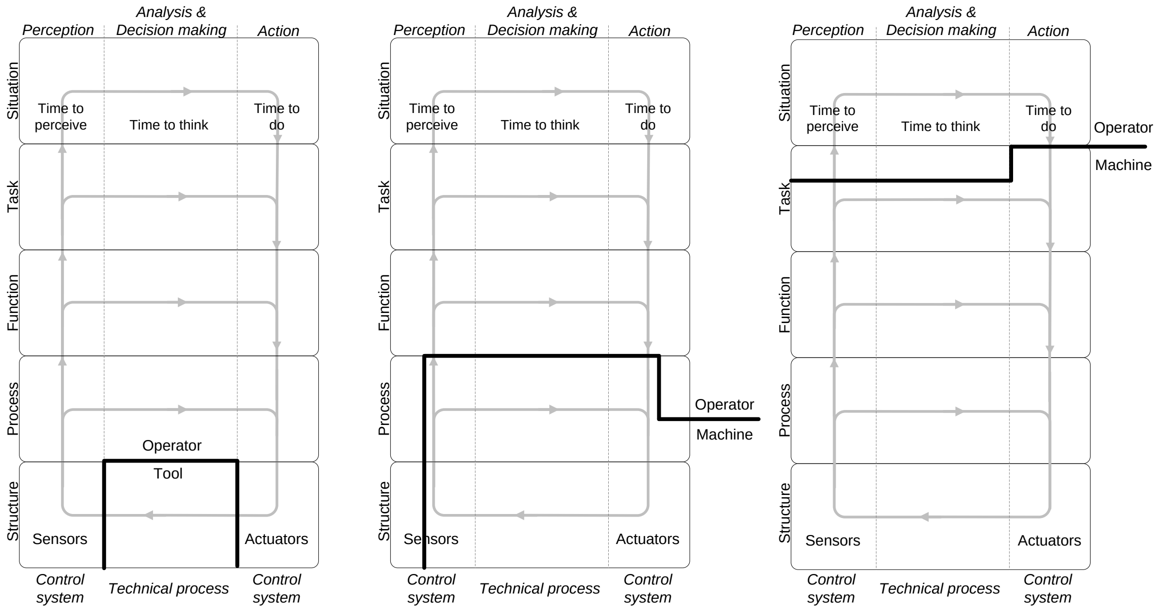

Figure 14 a, b and c. Levels of Automation – manual, semi-automatic and automatic carpentry

Summary

Chapter 4 has described the different model components; the means-ends hierarchy provides a basis for work domain description, the Perception-Action cycle as a control loop describes the control process and how information flows to achieve the goals of the work and the operational context is taken into consideration by using PIFs. It has also been shown how levels of automation can be illustrated in the model. By using a general framework to describe human and machine activities, the model is able to account for varying kinds of work situations. The next chapter gives a background to the nuclear power domain. This is followed by analytical and empirical results from using the model as a tool for analysis.

5
The Nuclear Power Domain

This chapter introduces the nuclear power domain. The domain is described briefly from a societal, organisational and operative point of view. A case study performed at the Studsvik nuclear power plant simulator training facility is also presented. This case study is the foundation for the analysis of empirical results presented in chapter 6.

5.1 Nuclear power from a societal perspective

In Sweden, nuclear power as an energy source to create electricity has been debated ever since the 1970s. The Swedish nuclear energy programme was initiated after world war two as an initiative to create a domestic production of nuclear weapons, but when the weapons programme was abandoned the nuclear programme continued as a civil energy project. In the beginning of the seventies the main debate concerned the nuclear waste. In 1979, only a year before the Swedish referendum on nuclear power, the accident at Three Mile Island power plant happened. This had impact on the opinion and the Swedish people voted for nuclear power to be gradually phased out until 2010. After the nuclear catastrophe in Chernobyl in 1986 the opinion against nuclear power was further strengthened, and renewed debates followed. Since then the opinion has shifted and today, in spring 2010 only 20% of the Swedish people want to abandon nuclear power as an energy source (Stiernstedt, 2010). In 1991, the decision to phase out nuclear power was torn up due to the economic crisis, since a lack of the nuclear energy sources was seen as threat to the competitiveness of Swedish industry. Currently, large investment projects are undertaken to increase efficiency and safety in the Swedish nuclear power plants. This development can be seen across the world where a large number of new power plants are currently built.

To maintain safety, the nuclear power industry is strictly regulated. The Swedish Radiation Safety Authority (SSM) monitors all nuclear technology activities in Sweden and works to ensure that safety work is developed and maintained in the nuclear facilities. SSMs role in nuclear safety can be illustrated by the events following the Forsmark nuclear power plant incident (Analysgruppen, 2007) on July 25th 2006, where safety barriers were breached due to a short circuit in a switchyard outside of the Forsmark 1 reactor unit. As investigations of the incident started, SSM prohibited Forsmark 2 and Oskarshamn 1 and 2 from starting since they are constructed in similar ways. SSM further made a critical review of the safety culture at the Forsmark nuclear power plant. It was concluded that the safety culture had deteriorated over the years, and thus SSM required the company to develop a plan of action for improvement of the safety management within the company. This way, SSM has the authority to monitor the nuclear power domain in Sweden and take measures to ensure that high safety standards are maintained.

5.2 Organisational impact on safety

In the nuclear domain, the organisations that manage the nuclear power plant facilities have an important role to maintain high safety standards. The organisation should assure that competence is withhold, both in the short term by training and educational efforts, and in the long term by seeing to that competence is not degraded in the organisation over time, for example due to retirements. The organisation also has to provide the prerequisites for safe operations by appropriate staffing, maintenance, operational support and withholding a safety culture. The term emerged after the Chernobyl accident and consists of the safety related values and attitudes shared by the members of the organisation (Bohgard & Dahlgren, 2009). This includes the formation of a 'learning organisation' (Senge, 1990) which actively collects experiences and learns from its own and others mistakes. A part of achieving a learning organisation in high-risk domains is to have a reporting system where members can report incidents and near misses. The incidents can then be highlighted and learned from, to avoid similar events in the future. A reporting culture however presupposes a blame-free culture that not seeks to find scapegoats, but instead sees the value of an open dialogue around problems seeking to improve all activities within the organisation.

5.3 Nuclear power plant control room operations

The nuclear process is controlled from a central control room. Here, information is gathered and the operators can monitor and control the objects in the plant and communicate with external personnel.

5.3.1 The nuclear power plant control room

In a nuclear power plant, each reactor with its turbine has its own control room. The control room shift teams consist of at least one shift supervisor, one reactor operator, one turbine operator and three field technicians (Jönsson & Osvalder, 2005). The shift supervisor manages the work. The operator roles, reactor- and turbine operator, also reflects how the control room is physically organized in a reactor side and a turbine side. The reactor (primary) side includes instrumentation and controls for the reactor and the reactor containment. The turbine (secondary) side consists of instrumentation and controls for the turbines, feed water system and the generator producing electricity to the grid. The turbine operator is also responsible for the switch board controlling the plant's internal power supply. As the name implies, the field technicians also work outside the control room performing checks and operations locally in the plant.

The nuclear power plant operators are highly trained and educated, mainly from internal education and simulator training. The control room operators has often started as field technicians and after several years of field experience proceeded as operators. The work rotation between roles is limited, but shift supervisors and some operators have the competence to operate on both the turbine and reactor side of the power plant when necessary. The supervisory control is highly dependent on a well functioning alarm system. The alarms trigger further actions and indicate critical states. The operators' work mainly consists of routine tasks and handling of well known situations (Jönsson & Osvalder, 2005). A challenge is however to handle unplanned and unknown situations that rarely happens.

Figure 15 The turbine control desk at Ringhals 4

In tightly coupled technical systems such as nuclear power plants, the controlled process with all its' physical and technical constraints, the operator has to learn and develop understanding of how to control the plant to achieve the desired output. It is the technology together with fundamental physical laws that directs what has to be understood to enable safe operations. This is a substantial difference compared with consumer products, where the interface should be designed to match the users existing understanding of how things in daily life normally work. In safety critical industries, the operator instead has to adapt, learn and construct a mental representation of how the technical process functions.

The operator needs a mental representation of what is happening in the plant to be able to control the process and to be able to plan and predict action outcomes. The operator also needs this representation to solve problems effectively (Stubler & O'Hara, 1996). The representation is gradually built up and has to be continuously adapted as the plant configuration changes over time. Since the operators start as field technicians, they acquire a thorough representation of the structure, location and functionality of the process equipment. The operators' knowledge is then further developed through the operator education and practical training in the control room and in simulators.

The main aim of shift-team training is to assure that personnel have the skills, knowledge and abilities necessary to perform their job in a safe and reliable way (O'Hara et al., 2004). To achieve high quality operator training, company management must define the learning objectives according to the knowledge that is necessary to operate the plant during normal, upset and emergency conditions. The team simulator training is an important means to refresh skills that seldom are used.

5.4 Automatic Turbine Operations in practice

To illustrate how automatic systems are used in practice in the nuclear domain, a field study performed at the Studsvik training facility is presented. The simulator was a full scope simulator, identical to the control room in the nuclear power plant. Figure 16 show an image of the power plant control room. The field study results give a background to the analysis of empirical results presented in section 6.3.

Figure 16 The control room at Oskarshamn 3 (www.okg.se, 2010)

5.4.1 The Automatic Turbine System

The ATS is divided into a hierarchy of different control levels that consist of superior-, functional group-, sub group- and object automation (Figure 17) (KSU, 2005). The superior automation controls the underlying automation through sequences. These sequences are programmed to take the turbine system from turbine axis standstill to full effect operation through a number of steps. These steps are presented in the superior automations interface in the control room. The automatic sequences give start and stop orders to the functional group automation and individual objects.

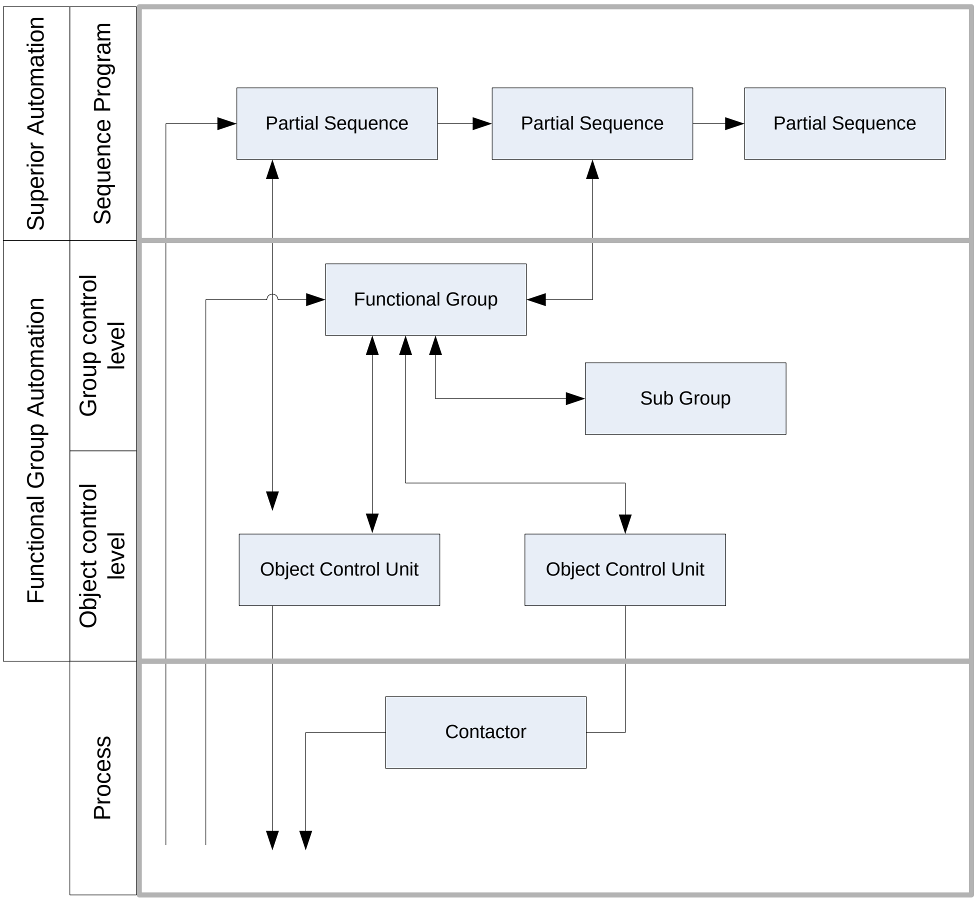

Figure 17 The ATS control hierarchy (Adopted from (KSU, 2005)

The start and stop orders are only executed if certain conditions in the process are fulfilled. Some of these conditions are presented in the ATS interface (Figure 18). In turn, the conditions relate to the underlying program logic. When a program sequence has been executed, a process response is sent back to the superior automation and the next program sequence is initiated.

The functional group automation is subordinate to superior automation and brings objects with an internal dependency together in subgroups. The object control is used if the operator needs to control separate objects manually, not using the program sequences. The sequence program is presented in the ATS-interface and describes in what order the automatic sequences will be started, and what conditions that are being supervised. The sequences declare where an automatic sequence should receive their start- and stop orders, and where each process condition has its monitoring area. To control the functional groups, sub groups and individual objects the operator uses the ’Manoeuvre and Indication Units‘ (M/I-units). The M/I-unit interface includes control buttons and lamps for status indication and they can be altered between automatic and manual operation. The M/I-units are placed on the control room wall panels in connection to the process mimics. When the superior automation is engaged, feedback is given both from the ATS-interface placed in the turbine desk and from the M/I-units on the control room walls.

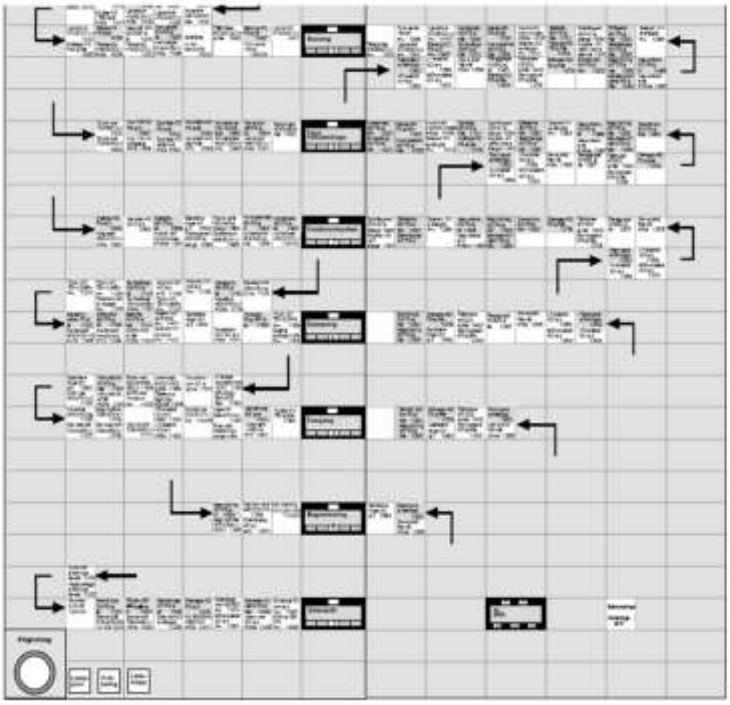

Figure 18 The ATS-interface, (Adopted from (KSU, 2005))

In the ATS-interface, the superior automation's sequences are presented (Figure 18). The automatic sequences are sorted into eight operational states; these are also called 'stable states'. When a stable state is reached, it is possible to maintain the power plant in this state. The stable states range from 0 to 7 where 0 represents 'Turbine axis standstill' and 7 'Effect Operation', meaning that the plant produces energy to the power grid. The turbine operator uses the automatic program sequences to start the turbine and follow procedures to reach effect operation, passing through the stable states. The stable states are also useful when an anomaly occurs and the turbine process falls back. The stable states let the process stay at the highest stable state possible.

With the immense number of individual objects in a nuclear power plant, the structure of how objects interact in the automatic sequences, through functional groups and sub groups, quickly becomes very complex and hard to overlook in full. The aid given by the ATS to handle a number of tasks is helpful to the turbine operator. In its design, the ATS-interface can be used as a hardwired procedure that lets the operator follow the turbine start-up and shutdown step by step.

In turbine operations, the operators mainly used three different LoA; manual-, step- and automatic mode (Andersson, 2008). In manual mode, the operators perform actions without using the automatic turbine system (ATS) interface. Instead, the operator manoeuvre individual objects from panels or screens according to written procedures to reach the intended process state. In step mode, the operators use the ATS interface to start automatic sequences and follow the actions until the ATS has fulfilled the sequence. The operator then evaluates that the desired process state is reached before the next sequence is initiated. During normal conditions this cycle is performed until the intended process state has been reached (i.e. either the generator is producing electricity to the grid or the turbine axis has come to a standstill). In automatic mode, the turbine operator initiates the ATS program sequences and the program is executed without operator interference. It stops when it has finished its tasks, or if it encounters sequence conditions that are unfulfilled or when program orders fail to execute. Feedback on what sequences that are accomplished is continuously displayed in the ATS interface, similar to the presentation in step mode.

5.4.2 Field study interview results

The data collection was made as a field study where turbine operators in simulator training were observed through mirror glass from the instructors' cabin. The observations were followed by semi structured interviews with seven turbine operators regarding their use of the Automatic Turbine System (ATS).

The results are presented in relation to the three LoA used in the ATS operations; manual mode, step-mode and in automatic mode. Quotations from the interviews are used to illustrate the operators' thoughts of the interaction with the system.

5.4.2.1 The ATS in manual mode

In manual mode the turbine operators control the individual objects one at a time or in functional groups, using the M/I-units on the control room panels without using the ATS interface. This mode also involves the automatic reserve start function, since the object control includes automatic monitoring and start of redundant objects in case of failure. The individual objects are manoeuvred according to written procedures to reach the intended process state.

During normal situations, the operator usually has enough time to analyse the situation, plan actions and choose the appropriate procedure. Below a number of statements are presented that highlight issues in the operator-automation interaction.

'Manual mode gives better possibility to follow the process, but the automatic system is still better in some cases'

The operators state that the possibility to follow the process is better during manual operation because they perform actions by hand. When performing actions manually, the operators read through the procedures when preparing to perform a task. This gives a direct update of the expected course of events and facilitates the anticipation of the following process responses. Therefore this should aid anticipation of events while the procedure can be used as a road map for events to pass in the near future. In manual mode the pace of actions is controlled by the operator and there is time to think and revise the situation. If an action does not give the expected result, this can thus be directly related to the action that just has been performed, provided that the time to feedback is short.

When the operators use the M/I-units (which can be said to be a low level of automation, although it is not manual by definition) the level of complexity is also reduced compared to the automatic sequences in the ATS-interface, where the underlying logic is at work. This reduction in complexity can also explain the facilitation to follow the process. While the M/I-units placed on the control room walls have a more visible link through the process mimics, it facilitates the ability to follow what response an action will produce.

The overall monitoring of process state may suffer from manual operations while the operator is focused on carrying out specific procedures. The operators mention risk of 'tunnel vision' if everything has to be performed manually. While strong focus on the task is needed, less time and attention can be spent on over-all monitoring. This means that attention has to be directed when needed, stressing the need for well designed cues. An increase in workload and stress can also occur, since more actions have to be done manually.

'Manual mode increases the possibility of human error'

According to the operators, manual actions increase the possibility of human error. While the manual operations are depending on human beings, the probability of slips, lapses and mistakes (Reason, 1990) when performing actions is larger than when the same actions are performed by an automatic system. In the control room setting, manual actions often includes following several pages of paper based procedures to complete a task. This means that the interface design has to be designed to minimize the need to keep information in the short term memory. It also needs to be consistent to avoid that similar actions give unexpected outcomes. At the same time as possibility of error is induced during manual actions, the feeling of control increase when performing actions manually.

Figure 19 shows how the conceptual model can depict the level of automation during manual operation. The figure illustrates how the control system is active in perception on the *Process* level, while the operator still has an important regulating function. The operator directs the physical objects by using the control system. Thus, the operator is an active part of the regulating loop.

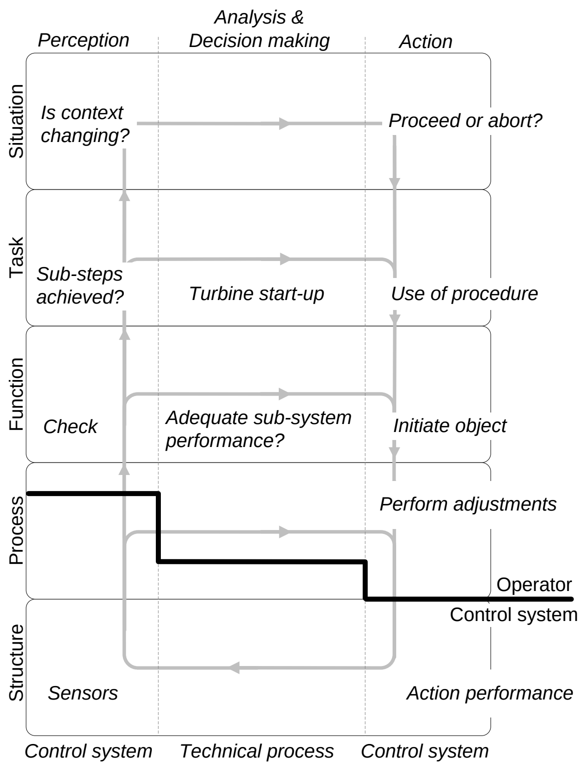

Figure 19 Turbine start-up in manual mode. The thick line illustrates the level of automation.

In manual operation, the relationship between action and feedback is clear. Verification of the process response using the procedure is also facilitated since individual objects can be followed closely. This strengthens the operator's knowledge and understanding of how the technical system works. However, since the operator has to be active on the *Process* level there is less attentional resources to maintain awareness on the *Situation* level.

5.4.2.2 The ATS in step mode

In step mode, the ATS performs all action sequences, but the sequences are initiated on the operators command (Figure 20). This gives the operator a possibility to control the ATS sequence by sequence at the same time as the automation's advantages of speed and accuracy are utilized. The operator follows the ATS program sequence, therefore the ATS control system is part of the *Task* level in as shown in Figure 20. The ATS notifies the operator by an indication in the ATS interface, if the turbine system has not performed a sub step accurately. Step-mode gives the operator time to think and assess the previous action in between the sequences. According to the operators, this combines feeling of control with the ATS speed and accuracy. The step-mode facilitates the human-control system cooperation, while the operator has time to perceive the position of the ATS, check the process status, and prepare the next program sequence by anticipating events in the near future.

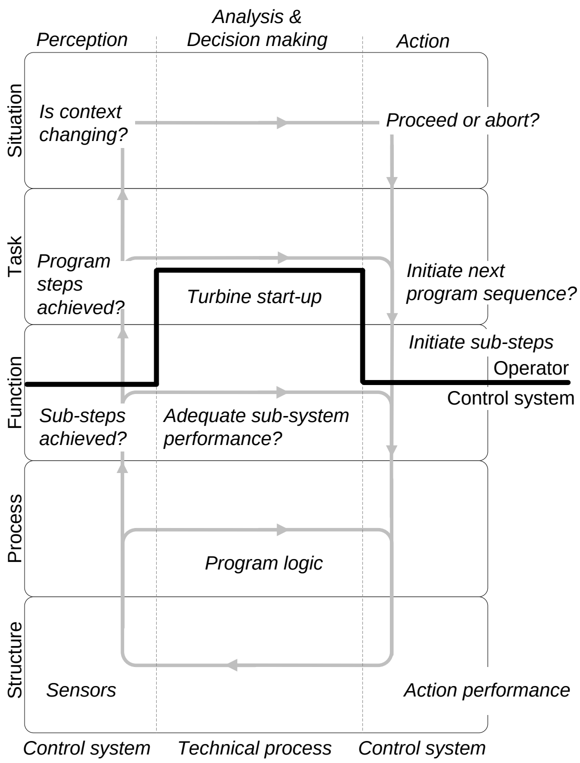

Figure 20 Turbine start-up in step mode. The thick line illustrates the level of automation.

Figure 20 illustrates how the turbine operator's work in step-mode can be described using the conceptual model. The *Structure* and *Process* levels are controlled by the ATS, while the *Function* and *Task* levels are partly allocated to the operator. The ATS provides information on a functional level, by indicating what steps that have been fulfilled. No information is however given on how the program logic works, since this is not needed as long as the ATS performs adequately. In the analysis & decision making step, the ATS evaluates the performed actions and indicates whether it is ok for the operator to proceed. In the action step, the operator initiates the step, which is performed by the ATS.

5.4.2.3 The ATS in automatic mode

Figure 21 show how the conceptual model can illustrate the level of automation in automatic mode. In automatic mode, the operator monitors the overall performance of the ATS. The ATS program sequences are performed on the operator's command but without operator interference. The operator engages the program sequences and the system stops when it has finished its tasks. The program also stops if it encounters unfulfilled conditions or if the process fails to execute program orders. Feedback on what sequences that have been accomplished is continuously displayed in the ATS-interface. The operator can thereby follow how the ATS work on the *Function* and *Task* level, but is further distanced from the regulating loop in the *Process* level.

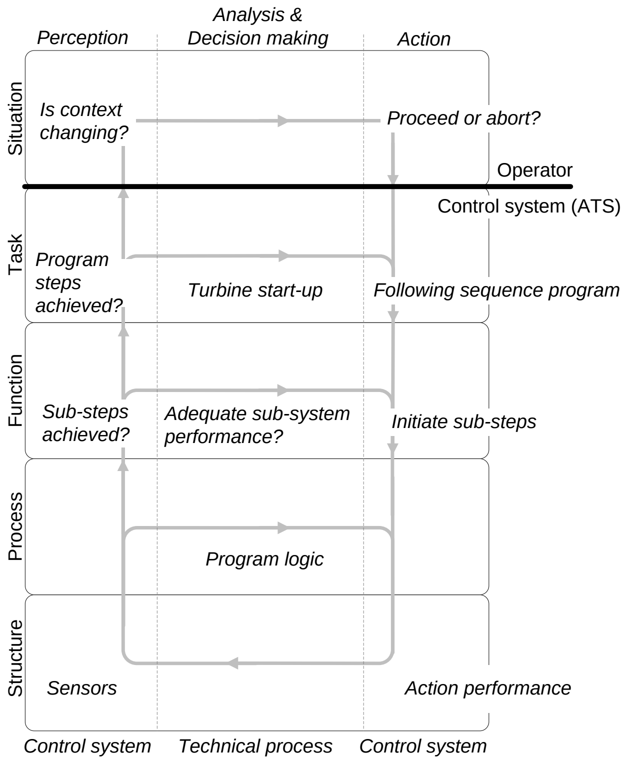

Figure 21 Turbine start-up in automatic mode. The thick line illustrates the level of automation.

'There is a risk that the automatic sequences run away from you, and you lose track in the procedures'

When asked about problems using the ATS in automatic mode, the operators express that the automation foremost affect them in the way that the automatic sequences are so fast that they are difficult to follow. The operators remedy to this is that they avoid using full automation and prefer using the step mode. The step-mode performs the same actions as in automatic mode but it gives the operator the possibility to check that the performed action has achieved what it should, by using redundant information sources (e.g. the wall panels). When using the step-mode, it also becomes easier to intervene and make changes if an action is not performed as it was supposed to. The operators also review procedures before implementing an action, in this way they have the expected outcome of the sequence to be engaged in, in fresh memory. This helps the operators to 'stay ahead' of the automation.

The operators also state that it is difficult to trouble-shoot a failure in the ATS and that the difficulty increases with use of automation. Due to the system complexity and the automatic system conditions with their underlying logic, make trouble-shooting activities very time consuming. When using step mode, finding the fault is easier since the operator actively engages in the control at the *Function* level. This gives a better idea of what has happened in the past and what position the ATS was in when the anomaly occurred, reducing the time to correct it. Since the ATS is efficient and often performs better than a human operator in terms of accuracy, speed and controlling several objects simultaneously, the operators are still prone to use automation as it fulfils their goals of operation in an effective way and rarely fails during normal conditions.

Figure 21 illustrates how the control function is allocated depending on the choice of LoA. In case of a failure during turbine start-up, the LoA is instantly changed from the normally used step-mode to manual mode since the use of the ATS has to be abandoned until the failure has been located. The ATS interface neither provides any information on the *Process* level. This type of information has to be collected from the control room panel walls, computers, paper based program sequence matrixes, and logic schemes. The shift in LoA means that the operator, from having had a monitoring role on the *Task/Function* level, has to become a part of the regulating loop on the *Process* level. When using the ATS, the operators are out of the regulatory loop and if a failure occurs, they have to work themselves into the loop by resolving the failure and reverting to manual control.

5.4.2.4 Operator comments on ATS interaction

During the interviews, deficiencies in the ATS design were discussed. These results relate more to usability issues than to levels of automation, and support the separation between levels of automation problems and usability automation problems as discussed in chapter 3.1. Below, the operators' comments are written in italic and are followed by a description of the perceived problem.

'The ATS doesn't show what it is doing'
When all ATS conditions are fulfilled, no lights are lit in the ATS-interface. This follows the 'dark-board principle' meaning that when no lights are blinking everything is normal. However, when a condition shifts from being fulfilled to unfulfilled and then back to fulfilled, this causes a quick blink in the ATS-interface. The ATS is not integrated with the control room event list, placed in the control room's main computer. This means that the blink is not logged. This can cause confusion according to the operators, while they catch the blink but when they go to the event list (which is the normal thing to do in other similar situations), there is no indication on what caused the blink.

'It's difficult to know what objects the automatic functions affect in the process'
The desired goal when engaging the ATS is in practice always clear; the operator wants to reach a defined process state. The objects that have to be engaged to reach a certain process state can be numerous and are not visible in the ATS panel. Instead, the operators monitor the control room panels and the process mimics for the series of events to pass until the desired state is achieved. However, if something goes wrong and the automatic sequence stops, it often becomes very difficult to trace what actually happen. The trouble shooting process is often complicated and takes time due to the system complexity. This can influence the time to get the power plant back on to the grid again, and therefore has direct economical consequences. This problem tend to get worse as the level of automation gets higher, since the operator's attention doesn't need to be strictly focused on the task being performed by the ATS. The fact that the ATS panel only gives text based information on what objects that are affected in the process can also explain this comment to some extent. Integration with a graphical representation of the process would probably improve the operators' ability to match the object to their mental model of the plant.

'If you make a small mistake, you can be caught standing with your pants down'
This comment refers to one of the operator explaining how he, when handling the ATS-interface during a test program, caused a turbine scram. In the handling of other systems in the control room, it is not necessary to accept an alarm immediately. You can still control the plant and nothing happens because of the unaccepted alarm, the alarm is just indicated as unaccepted. In this scenario, the operator started a program sequence without accepting an underlying condition. To make the unaccepted conditions visible the operator has to press a button to light the conditions up in the ÖA-interface. This means that an extra action has to be performed by the operator to make the unfulfilled conditions visible. The operator started the program sequence without performing this action and therefore not knowing that there was an unfulfilled condition in the sequence. This in turn, caused the turbine scram. Similar events have also happened during simulator training. This shows how different factors together can cause an unwanted event. First, the consequence of unaccepted conditions varies in different systems. The handling of conditions in the ATS interface and other alarms are not consistent. Secondly, the operators use the ATS very seldom, which causes insecurity and problems with remembering how the system differs from other systems. The third factor is problems with observability in the ÖA-interface. It is difficult to get a full overview of the ATS actions while not all parts that affect the operation are visible. The process response, the automation's conditions and the automatic program with the underlying logic can be said to lie in different layers in the ATS interface. These layers are highly linked but cannot be displayed at the same time in the interface which causes visibility and use problems.

'It is difficult to see for how long a condition is fulfilled'
In the ATS program sequences the conditions that have to be fulfilled for the ATS to continue are monitored by the system. When a condition is fulfilled, the program continues. The condition can shift between being monitored by the ATS and being fulfilled. This discrepancy can be seen in the ATS panel using buttons that light up the conditions. The operators state that it is difficult to see for how long a condition is fulfilled. This information is important to know when engaging the automatic system to perform a task sequence. If a certain condition is not fulfilled in an automatic sequence that is about to be engaged, this can lead to the ATS automatically returning to a lower stable process state. These fallbacks are unwanted while they require additional time to get the plant back on the grid.

5.4.3 Strengths and weaknesses in the ATS

During manual control, the operators mention loss of speed and accuracy in performing actions, and difficulties to divide attention between performing a task and overall monitoring as the major problems. The positive aspects of manual operations lie in increased feeling of being in control when performing actions by hand. With higher levels of automation the problems shift to issues concerning difficulty of following the automatic sequences and loosing track in procedures. As the level of automation gets higher, information presentation also becomes more important. The semiautomatic, step-mode is often used by the operators since it combines the speed and accuracy of the automation with the ability of maintaining the feeling of being in control. Further, a number of usability related concerns was found in the ATS interface. The operators especially mentioned the presentation of the conditions that manage the automatic sequences as difficult to perceive. This may also cause costly errors due to presentation problems and inconsistencies compared with the handling of other systems in the control room.

6

Describing automation usability problems

This chapter presents how the model can be used to describe automation usability problems. The chapter first presents analytical results where the model is applied on automation problems presented in theory. The second part of the chapter presents empirical results where the model has been applied on the results from a case study of the nuclear power domain.

6.1 Using the model to analyse automation usability problems

The main idea of this work was to show that many of the problems that occur when humans and machines work together can be understood by studying the difference between the operator's mental model and how the technical process actually works in reality. This idea is particularly useful when studying the interaction between operators and control systems, since the operator is distanced from the technical process and acts through the intermediary control system. As the operator acts on a distance, a mental model that matches reality is important for effective control and problem solving. Without a mental model that matches reality, there is a large probability of degraded performance. In the case of human-control system interaction, model mismatches can be effectively masked by the autonomy of the control system. The masking and the degradation of the operator's mental model over time is not necessarily a problem as long as the control system work as it should. When the automatic functions fail, the mismatch however becomes apparent.

Figure 22 illustrates how the conceptual model introduced in chapter 4 can depict model-reality dissonance at different levels of abstraction. At the *Structure* and *Process* levels the operator's image of how the technical process works and how it is regulated needs to match reality if the operator should understand what happens in detail in the technical process. A model-reality mismatch may lead to difficulties in problem solving. On the *Function* level, a mismatch can lead to, for example, incorrect beliefs of what the technical process can perform. It can also lead to that all functionality is not used if the operator is unaware of it. On the *Task* level, a mental model that corresponds to reality is necessary for the operator to plan work effectively. This is related to how the technical process behaves over time. On the *Situation* level, the operator needs an accurate mental model of how the technical process is related to its context, to be able to foresee what effects external disturbances might have.

As Figure 22 describes, the control system and the technical process, shape the operator's mental model as the operator learns how the technical process is working. The mental model in turn directs the operator's actions, since the model works as a base in the operator's decision making process. The mental model is a dynamic construct that changes over time. Reality however often appears to change more rapidly, for example during technical malfunctions. This change may go on for a long time before it becomes observable and has a noticeable effect on operations. The operator then has to update the mental model to the new conditions.

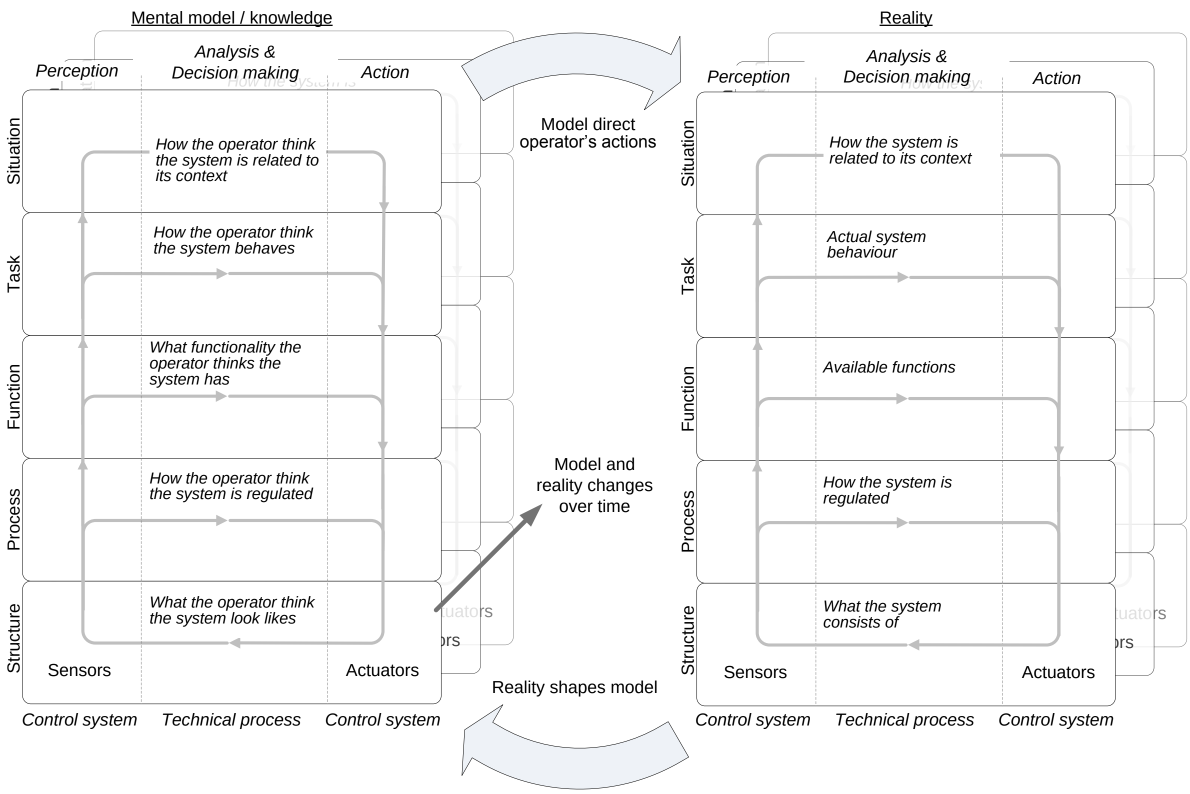

Figure 22 Model-reality mismatches that may lead to degraded operator performance

The main purpose for using a dual model (mental model vs. reality) is to make clear how a mismatch between mental model and reality may cause problems, and that automation-usability problems can be explained by using this approach. The conceptual model should be used by first analysing the work domain (e.g. the power plant), for example in the design phase before it is taken into operation, to elicit what the structure of the operator's mental model in general should look like on different levels of abstraction to match reality. The operator's mental model can then be shaped through education and training. Further, the operator's general model can be withheld by an appropriate control system interface based on the same structure. The model can also be used for analysis of existing human-machine systems on a general level, as will be shown in section 6.2 and 6.3. It is very important to note that the purpose is not to examine the operators' mental models in detail, since it is difficult to assess mental models in detail. (If the techniques for mental model elicitation are improved, the model can however be adapted to this in the future.)

In this chapter, the model proposed in chapter 4 is used to map three examples of automation usability problems (out-of-the-loop, loss of skills, and trust) onto the model using a general approach. The mapping is made to show that the model is capable of accounting for problems that often are described as unique phenomena in the human factors research base. The descriptions are divided into two parts. In section 6.2, the model is used analytically on the out-of-the-loop, loss of skills and trust problem respectively. The data used in 6.2 is taken from literature. Section 6.3 consists of empirical results with data taken from a case study performed by the author (Andersson, 2008). The purpose of the empirical section is to verify and strengthen analytical analysis, i.e. to show that the automation usability problems occur in the nuclear power plant domain and that the conceptual model is useful to analyse empirical results.

6.2 Analytical results

Out-of-the-loop, loss of skills, and trust were chosen on the basis of being well known and they are typical automation usability problems that also can have critical implications for systems safety. The other automation related problems described in section 3.2 were left out due to the limitations of this thesis.

6.2.1 Out-of-the-loop

The out-of-the-loop problem is maybe the most common and well known automation related problem that also creates other problems (Figure 8). It mainly stems from disrupted feedback and can in turn create loss of skills, deteriorated situation awareness and diminish the operators' abilities to form correct expectations of system behaviour (Lee, 2006).

In the conceptual model, out-of-the-loop is described in relation to the levels of abstraction since the levels of abstraction provides different types of feedback to the operator. For example, in a power plant, control on the *Structure* level is exerted by operating individual objects such as pumps and valves, either through the control system interface or directly on the physical object. The feedback provided from this level is information from the individual objects, e.g. pump on or off, and valve positions.

Control on the *Process* level is typically exerted by setting parameters, e.g. flow, pressure and temperature of media active in the process (feed water, lubricants, steam etc.). The process is dependent on the correct functioning of individual objects. The feedback provided is related to the parameters. Information given over time through trend curves is generally essential process related information.

On the *Function* level the aggregated performance of objects and processes provides the needed functionality. For example, to achieve a cooling function in a boiler system the flow of water (*Process* level) must be kept at a desirable level. Too much flow will cool the boiler too much, hence reduce efficiency, and too little flow imposes a risk of overheating. Thus, the flow needs to be kept constant in relation to the delivered heat. This is mainly achieved by running pumps and opening valves (*Structure* level). The *Function* level generally concern sub-systems aggregated by several objects. The feedback from the *Function* level consists of information on whether the sub-systems fulfil their purpose, e.g. keeping the boiler temperature at an optimal level.

On the *Task* level, control is exerted by achieving close term goals defined by the task to be performed. Typical tasks with multiple steps in a nuclear power plant are start-up and shut-down and periodical tests. Feedback from this level consists of the desired goal being achieved by performing the complete task sequence. In the nuclear domain, procedures are a useful tool that also indicates what feedback from the *Structure*, *Process* and *Function* levels that can be expected when a task has been performed.

Control on the *Situation* level is maintained by judging whether the overall status of the plant is acceptable. Examples of situations are normal, deviating and critical situations that can be determined either from aggregated information from overall functions or from a few parameters that are critical for system safety (i.e. flow of coolant in a power plant).

When the control system is used to exert control on the *Structure*, *Process* and *Function* levels by controlling objects, altering set points and maintaining functions by use of control algorithms, the operator has to rely on visual feedback provided by the graphical user interface in the control room. Depending on the control system interface and the speed and complexity of the automatic functions, the operator may have difficulties to perceive the control actions taking place on the *Structure*, *Process* and *Function* levels. The operator has to rely on aggregated information of overall status. This does not pose a problem as long as the automatic functions works accordingly, but may cause problems if the functions fail and the operator is unaware of what has happened and thus does not know how to react. Figure 23 illustrates how the operator's knowledge is affected in contrast to the control system activities during use of automatic functions.

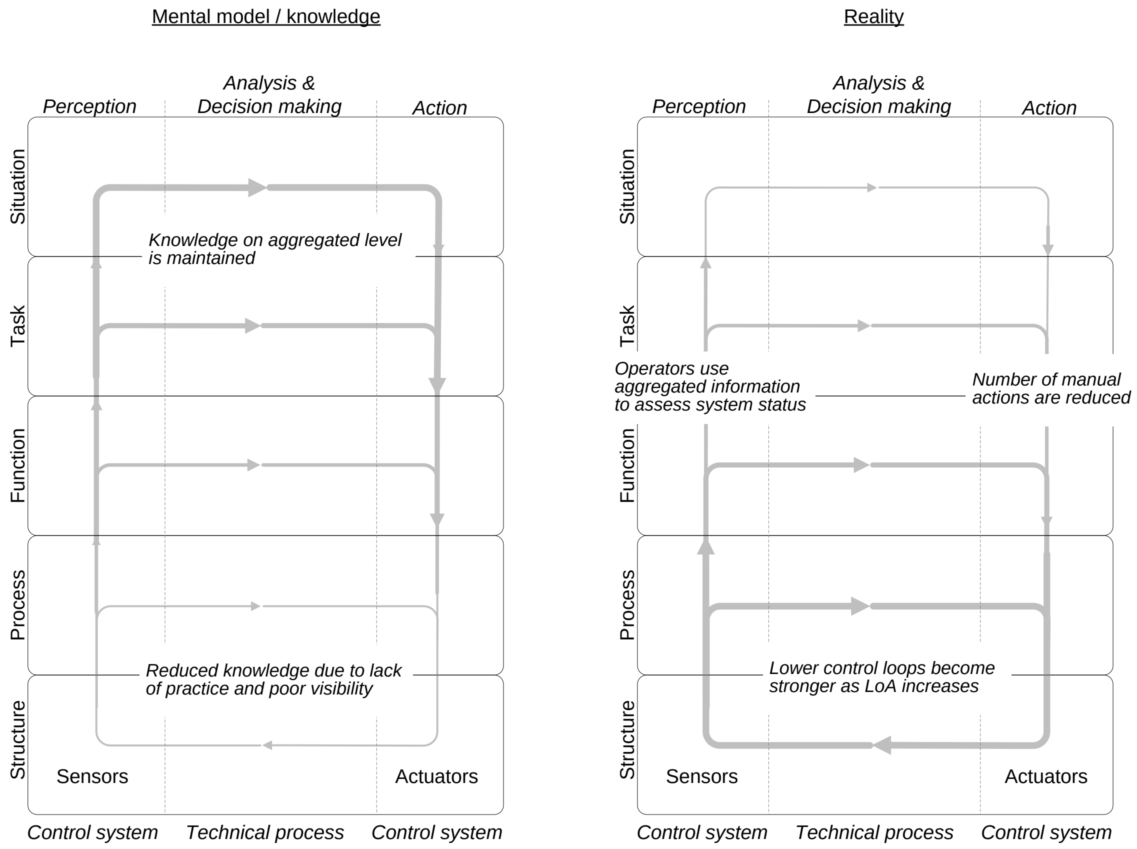

Figure 23 Operator knowledge in contrast to control system activity during use of high levels of automation

Since the operator in the control room is distanced from the process and has to rely on the graphical interface to follow the actions performed by the control system, information is a key aspect of the out-of-the-loop problem. To support the operator, the control system should help the operator to stay in the loop, i.e. aid perception of what is happening at the *Structure* level. This still presupposes that the operator is monitoring the control system interface regularly to be prepared for what may happen. A reliable automated system however fails very rarely, which implies that operators trying to perform their daily work as efficiently as possible should not pay too much attention to a system that performs on its own, since this gives operators time to do other things. Being out of the loop then becomes a natural part of operator work. The operator's ability to work him/herself quickly back into the loop then becomes very important. Thus, the control system interface should support this process of regaining an updated mental model to facilitate quick problem solving in case of failures.

6.2.2 Loss of skills

Loss of skills may occur because of how the operator's mental model changes over time. The change in mental model can occur as a result of how work, that operators previously performed using a low level of automation, is being automated and thereby imposing a risk that manual skills are forgotten. The operators however need these skills in case of control system failures when the operators have to revert to control on a lower level of automation. This is illustrated in Figure 24. During low level of automation, emphasis is on the regulatory loop at the *Structure* and *Process* level, and since the operator is actively engaged on this level of abstraction, the detailed knowledge is maintained. There is however, an increased probability that the operator fails to maintain an overall awareness on the *Situation* level in a short time perspective since much of the attention resources have to be directed to manual actions.

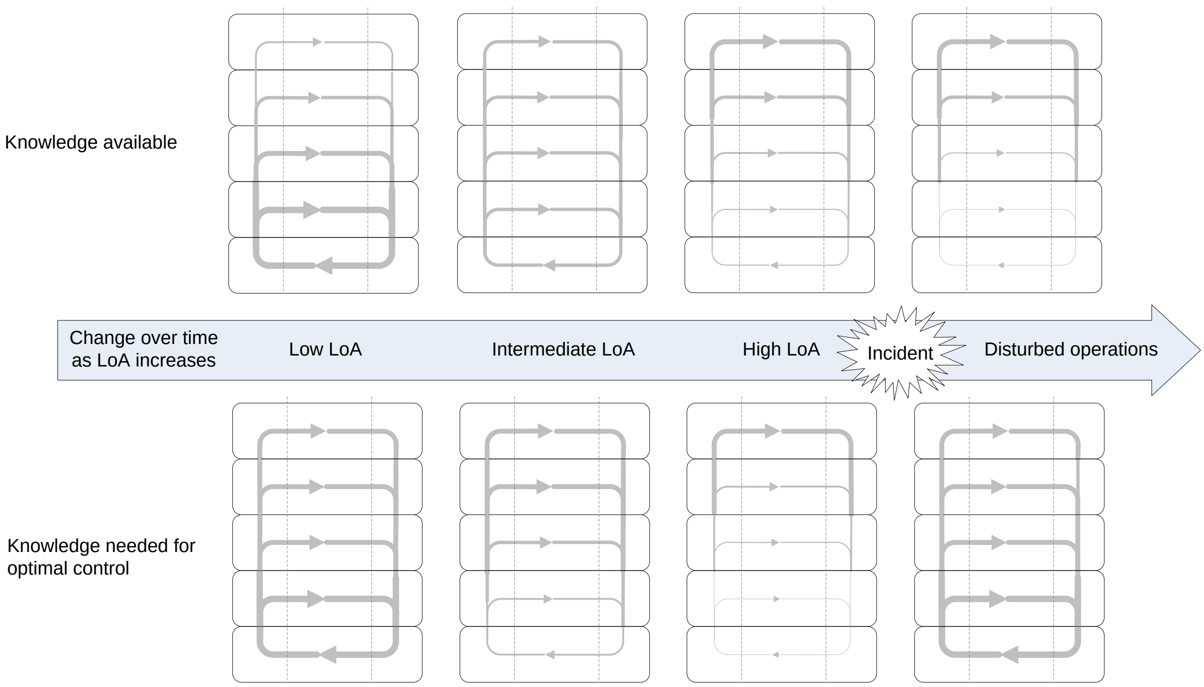

Figure 24 Loss of skills and the resulting difference between available and needed knowledge

During use of intermediate LoA, the operator does not need such extensive knowledge on the *Structure* level, since this is taken care of by the control system. Emphasis is then moved up to the *Function* and *Task* level. During use of high levels of automation, the operator does not need information from the lower levels in the model since the control system performs control. The operator mainly monitors that the control system achieves the task goals and that the overall situation is under control. Therefore, knowledge fades. If an incident happens in this state, there is a sudden need for knowledge of what has happened and how things work at the *Structure* level, and consequently the operator has to rebuild his/her model at the *Structure* level.

6.2.3 Trust

The origin of miscalibrated trust can be described as a dissonance between the operator's mental model of what the technical process can achieve, and what the technical process can actually achieve in reality (Figure 25). When the operator's mental model attributes larger functional capability to the technical process than the technical process can actually achieve, there is a risk of overreliance. Similarily, when the operator's model attributes too little functional capability it may cause underreliance. Trust is then shaped primarily by what the technical process achieves and if that performance matches the outcome that the operator has expected. Trust is therefore mainly formed at the *Function*, *Task* and *Situation* levels in the model, and can be seen as a result of a mismatch between the operator's mental model and actual system performance. The temporal specificity is then the frequency by which the operator can adapt his own model to reality. This probably also includes an element of meta-cognition, as the operator has to be aware of his own trust dissonance.

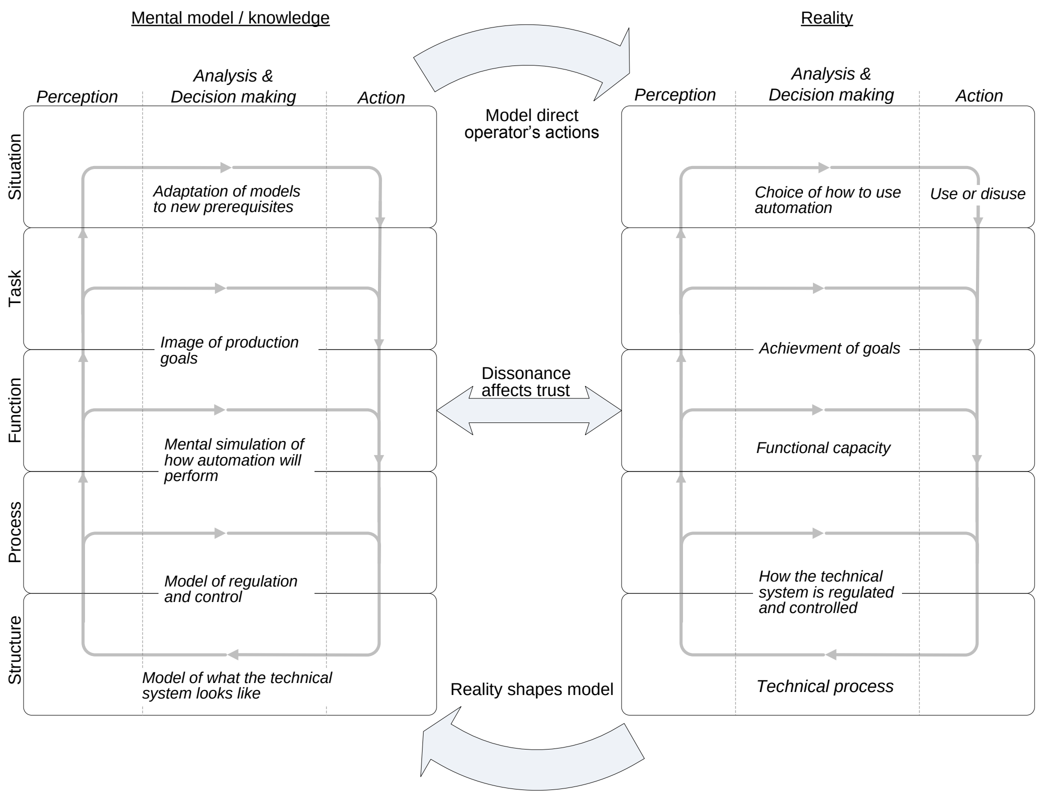

Figure 25 The formation of trust described as dissonance between operator model and real performance

6.3 Empirical results – analysing nuclear power plant turbine operations

This section presents how the model can be used to analyse empirical results from observations and interviews in control room settings (Andersson, 2008; Andersson & Osvalder, 2008, 2009; Bligård et al., 2010 (In press)). In chapter 5.4, the use of turbine automation in a nuclear power plant was described. It was explained how the operators experienced out-of-the-loop problems and loss of skills due to a poor automatic turbine system (ATS) interface. It was also described how the turbine operators balanced their performance by reverting to a lower LoA, and the different LoA used were illustrated using the model.

In this section, the analysis will be taken a step further in order to show the use of having a systemic model for analysis of supervisory control. In addition to the interview results regarding problems related to turbine operations presented in section 5.4, a few organisational factors will also be taken into account in the model. The background of the organisational factors used in the analysis is described in Paper 1. To show that the model can be used not only for problem descriptions, but also for normal operations, the analysis will start by describing turbine operations during normal operating conditions and then move on to problems the operators experienced during use of the ATS.

Figure 26 illustrates the operator's work during turbine start-up. To begin with, the operator has control over time, since the ATS pause after each sub step. Thereby the operator has time to read, check and evaluate before initiating the next program step. As the operator initiates a program step, the ATS control system initiates the objects necessary to fulfil the program step. The operator can follow this on the control room wall panels and in the control system computers. The operator then evaluates whether the technical process is in a state where the next program step can be initiated, which includes collecting information from other sources concerning objects that might affect the next program step.

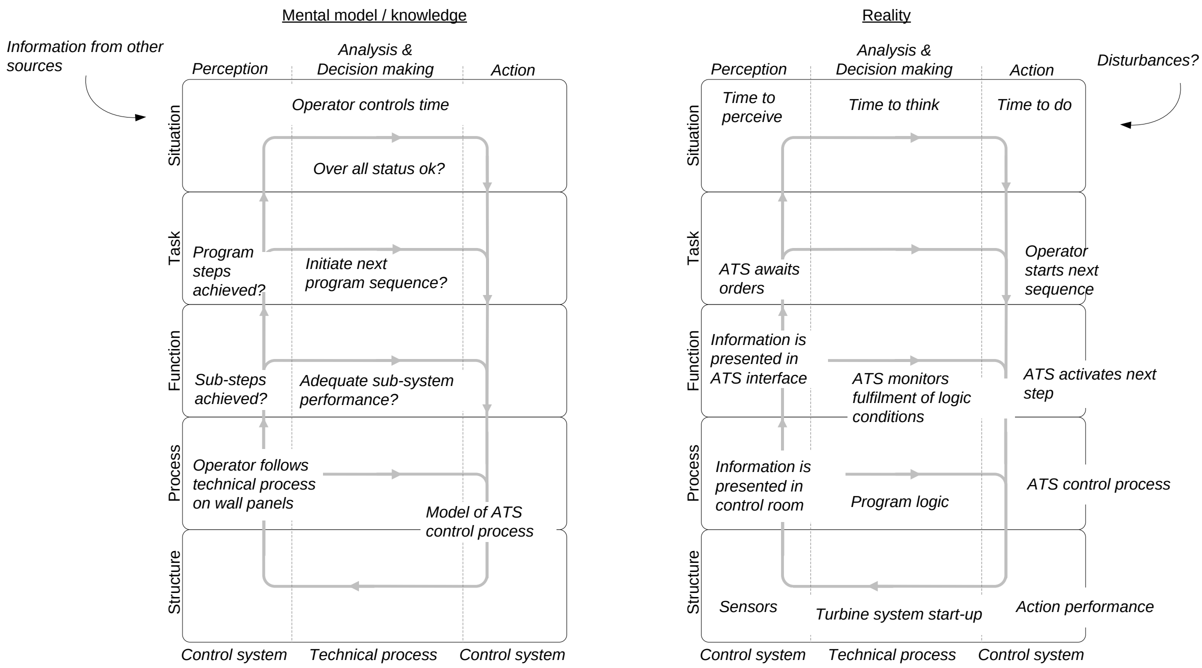

Figure 26 Turbine operations during normal operating conditions

During normal operations, the ATS performs as it should. Therefore, the operator does not have to use his/her model of the ATS control process (i.e. conditions and logic necessary to proceed in the turbine start up). Knowing what objects that are engaged and following the ATS work in the ATS interface is sufficient to reach the intended goal of getting the generator phased onto the grid. When the operator has to revert to a lower LoA, the situation however changes and problems may occur.

The difficulties that occur when the automatic functions fail can be argued to come from that the necessary knowledge is not available to the operator, not in the head, nor easy accessible in the world. Since the complexity of the logic schemes controlling the ATS on the *Process* level is immense, there is however no reason to demand that the operator should have such a detailed mental model. Instead, the control system interface has to function as a cognitive off-loader and aid the operator in his/her search for information. The operator searches for the information when the situation demands it. Thereby the operator makes his/her mentalmodel more complete by adding details regarding the ATS program logic from other information sources. This can however be a very time consuming process due to the complexity of the sequence program matrix and logic schemes.

The LoA affects the operator's mental model by relieving the operator from actively using the mental model continuously. In turbine operations, the LoA changes quickly in discrete steps. A degraded mental model can not recover in that short time, therefore a dissonance between the operator's mental model and reality may occur that can lead to problems. When the ATS fails, the operator needs knowledge that not has been needed for a long time (or ever) and the operator has to recover this knowledge from other representations such as schemes and procedures. The operator and ATS model dissonance when the ATS fails can be illustrated by using the model as shown in Figure 27.

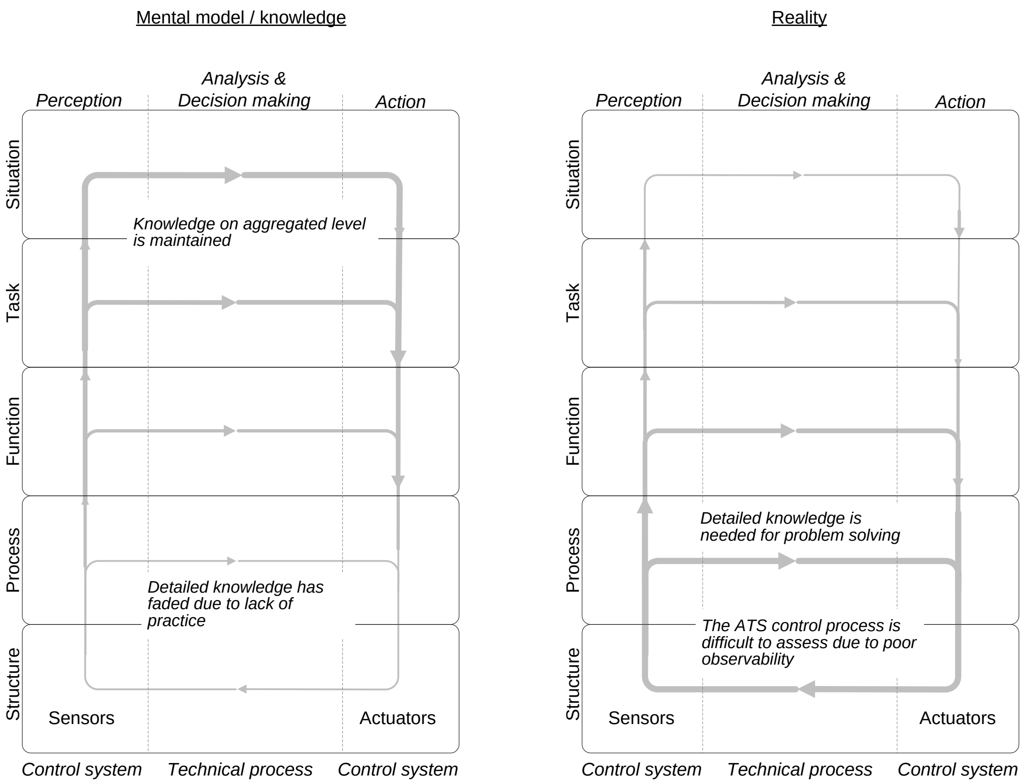

Figure 27 Operator model and ATS-system dissonance

The operator's mental model is also shaped by what the operator sees and does during daily operation and during simulator training. Due to the poor observability of how the ATS control process works, the operator never gets the chance to learn what happens on the *Process* level by using the ATS interface. Some feedback is provided by the ATS interface on what objects that are affected by the automatic sequences, but the operator still think it is difficult to assess effect of a program step before it is initiated. This relates to usability aspects of the ATS interface. For example, while the ATS interface is presents program steps on the *Function* level with poor connection to how each step relates to the *Process* and *Structure* level, the interface observability becomes reduced. Thereby the operator can not rely on the interface to maintain his/her mental model. Usability issues can also partly be regarded as an organisational PIF, since usability is assured during the development processes in the company. To achieve sufficient usability, the company needs competence to evaluate the solutions provided by the control system supplier. Adequate competence is also necessary to set the adequate usability requirements to be met by the control system supplier. This makes usability an organisational issue that will have effect on operations.

The simulator training sessions provide valuable occasions to maintain knowledge and skill in the operation of a nuclear power plant, both during emergency situations and situations that are planned but infrequent. Yet, operators stated that because the training only takes place once a year, there is a feeling of insecurity when having to perform critical actions in live situations. From a productivity perspective, the start-up and shutdown sequences should optimally occur once a year during the outage period. In these situations, the turbine operator uses the turbine automation interface extensively. The full start up/shut down sequence normally takes two working shifts to accomplish. There are seven working shifts at the power plant, which means that the turbine operators off duty will miss the opportunity to practice in the live situation. Because of the number of shift teams and the rare opportunity to practice, there is a risk of missing the start up/shut down occasion several years in a row.

During simulator training, tasks that require use of the ATS interface are occasional depending on the focus of the training session. The rare occasions of using the ATS in live situations together with occasional use of the ATS during simulator training imply a high probability of skill degradation in usage and understanding of the ATS (Figure 28). In simulator training, this must however be traded against the time needed to practice emergency situations that have a higher safety related priority. Since the operators have few occasions for practice there is high probability that they lose skill and knowledge over time. In the nuclear power domain the extensive use of procedures, however counterbalance the consequences of skill loss.

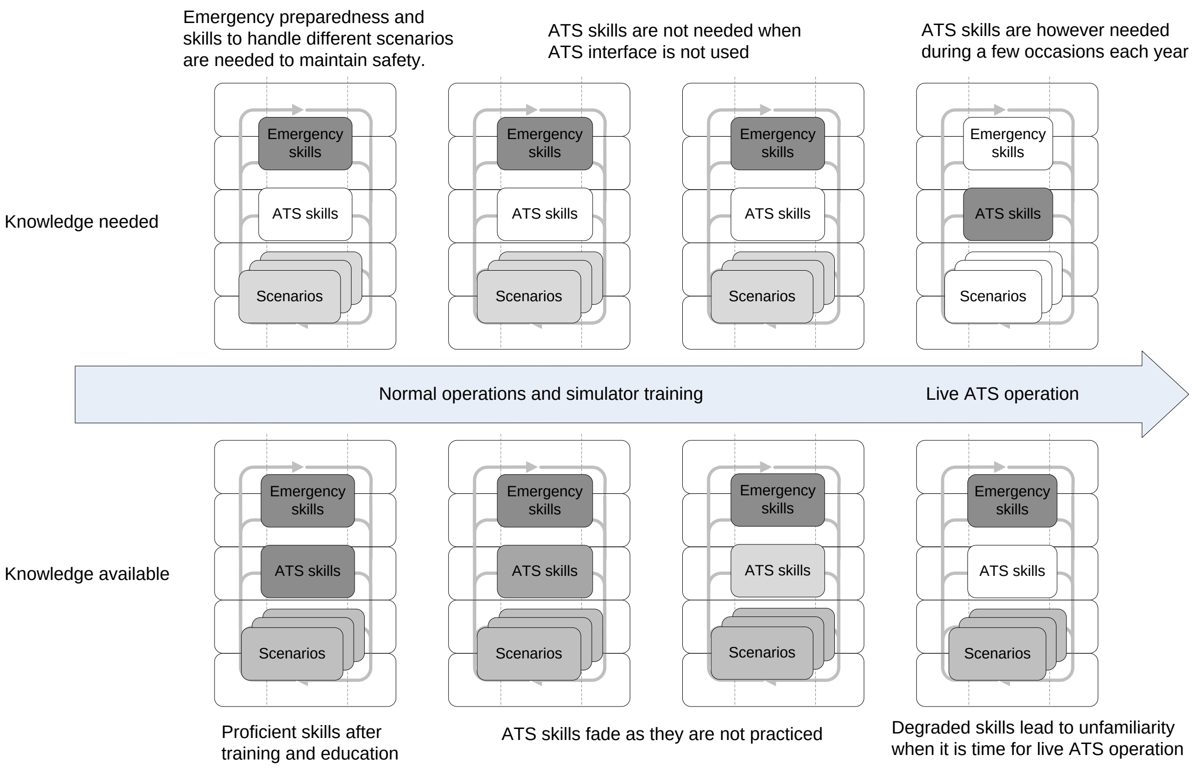

Figure 28 Loss of skill in turbine operations due to lack of practice during training and live operations. Dark color indicate proficient skills while light colors indicate faded skills.

Figure 29 further illustrates how the operators experience difficulties of following the ATS actions and understand how the control process works. This can be attributed to the poor observability of what the automatic functions perform on the *Structure* and *Process* levels in combination with the factors of training and practice discussed above.

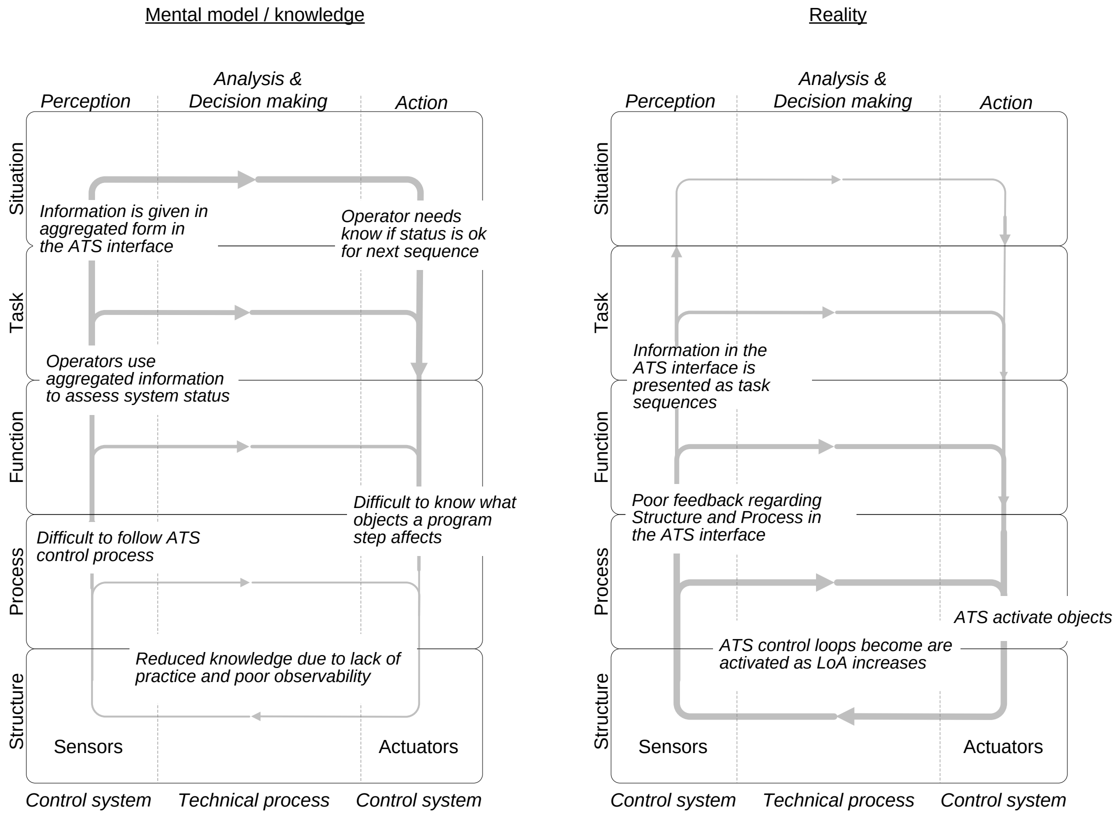

Figure 29 The out-of-the-loop problem in turbine operations

Summary

This chapter has shown how the model can be used for analysis of automation usability problems known from literature. To exemplify the use of the model, the out-of-the-loop, loss of skill and trust problems were analysed. In addition, the model was used for analysis of automatic turbine system operations using data from a field study. The results show that it is possible to use the model to illustrate why problems of this type can occur during use of automatic systems. The results also indicate that information from different levels of abstraction is necessary to maintain control and avoid automation usability problems in complex control systems. The role of interface design will be further elaborated in the discussion in chapter 7. The intended users of the model will also be discussed.

7
Discussion

This chapter discusses whether the aims and the purpose of the thesis have been fulfilled. Characteristics of the proposed conceptual model and its intended use are also discussed.

7.1 Fulfilment of aims

The purpose of this thesis was to contribute to the design of safe and effective human-machine systems, by proposing a conceptual model that can be used by engineers in industry as guidance in analysis and design. The aims were (I) to propose a conceptual model that capture aspects of human-machine interaction that are relevant for analysing automation-usability problems, and (II) to use the conceptual model for analysis of automation usability related problems and explain the emergence of different types of problems in a single framework.

In chapter 6, arguments for how the model is capable of capturing the important and problematic aspects of control room work was presented by exemplifying how the model can be used. The fact that each of the model components are used within the scientific human factors engineering community, further contribute to a solid model foundation. The existence of components that functions well separately do however not guarantee a well functioning whole. Hierarchical multi-loop models have however also been proposed before (see (Sheridan, 2006) for some examples), so also for the conceptual model as a whole there is support for this type of model approach. Rasmussen and Lind (1981) also state that '*the multilevel modelling framework can be used as the common denominator for the computations in the computer and the activities of the operator*' ((Rasmussen & Lind, 1981), p. 89), which is what the model presented in this thesis aims at achieving, although 'the computer' is here entitled as 'the automatic control system'. This means that aim one (I) can be considered to be fulfilled.

By using the model, three examples of problems that can cause degraded supervisory control were described and explained in the results chapter. Considering the general applicability of the abstraction hierarchy and the control theoretic approach to modelling, it is plausible that also other instances of human-control system related issues can be successfully accounted for. Due to limitations of this thesis, only three examples have however been provided in the results. In the theory chapter, clumsy automation and automation induced errors were also mentioned. In the model, clumsy automation can be described as the operator being forced to deal with the technical process on a lower level of abstraction than what is optimal considering the contextual factors, (i.e. PIFs). If the operator has to deal with details on the *Process* level, while attention is needed on the *Situation* level, it can lead to loss of control. Brittle failures can be described as emerging from lack of information on how hard the automatic system has to work on the *Structure* and *Process* level to keep its parameters within the system constraints. If this information is not provided on the *Function* level, there is a high probability that the operator will not notice what is going on until the automatic system collapses and the whole function is lost. Configuration errors can on the other hand be seen as how the constraints that direct the automatic system are invisible on the higher levels of abstraction where monitoring takes place. Mode awareness and automation surprises have similarities to the instances just mentioned. The high autonomy but low observability of the automatic system's actions and intentions relates to how information from the lower levels in the abstraction hierarchy can be made visible on more aggregated system levels. Since the model can account for several problems of the types described above, there is confirmation of that the model can be used for analysis of problems related to human work with control systems. Hence, aim two (II) of the thesis can be considered to be fulfilled.

7.2 Intended users of the conceptual model

The intended users of the conceptual model are persons who are involved in design and evaluation of human-machine systems in the industry. In the area of control rooms in general, and the nuclear domain in particular, the target group for this work is the people that design DCS (distributed control systems) and SCADA (supervisory control and data acquisition) system interfaces. This means people, or groups of people that are working in industry, either as system developers at the vendors of DCS and SCADA systems or as consultants that are engaged in making custom changes to, already implemented or to be implemented control systems. To use the proposed model in its full potential they will need background knowledge of human factors engineering and cognitive ergonomics to facilitate the reasoning around how humans, technology and organisations affect each other and functions as a system.

To achieve a description of the system that should be controlled, a number of methods can be used for analysis. In the three bottom levels in the model, Work Domain Analysis (Vicente, 1999) can be used to produce a means-ends hierarchy that mirrors the technical system and the goals and purposes that are inherent. In the *Task* level action step, task analysis methods such as hierarchical task analysis (HTA) can be used initially to achieve task sequence descriptions to reach the goals defined in the work domain analysis. The HTA can then be complemented with decision analysis tools such as Rasmussen's decision ladder and the SRK framework (Rasmussen et al., 1994). Cognitive task analysis methods can be used to complement the procedural sequences retrieved from the HTA, for example by using Applied Cognitive Task Analysis (ACTA) (Militello & Hutton, 1998). Interview methods such as ACTA are valuable as a way to elicit information from domain experts. To account for situational factors the PIFs can be used. These however serve as a checklist of known influencing factors, and does not account for unknown matters. The use of these methods to fill the model with content is important, but it is outside the scope of the thesis to go through the methods in detail.

As was suggested in the results chapter, the different levels of abstraction in human-control system interaction can be used to guide the content of control system interfaces. The choice of labels of the hierarchical levels was also made with respect to this intention (Figure 10). Most often, all the levels have their representations also in present control rooms since they are needed for control, although it may seem as if it has evolved from needs of efficient control rather than from a deliberate intention of representing different levels of abstraction. For example, additional sources of information are added in retrospect to meet the information needs of the control room teams, rather than having been foreseen in the design phase. If these needs can be foreseen, the creation of better integrated systems for control and information retrieval can be created. If different levels of abstraction and decomposition are included as natural part of interface design this will also most likely aid problem solving activity and the need for operators to work themselves smoothly back into the loop. Rasmussen et al. have shown how problem solving activities tend to go on the diagonal in a abstraction-decomposition space, until the failing component has been found (Rasmussen et al., 1994). This probably holds also for finding anomalies in automatic control systems, and therefore the multilevel approach to interface design is an alternative for interfaces that should support problem solving (Rasmussen & Goodstein, 1985). Jamieson et al. (2007) have also suggested use of Physical, Functional and Task related control system interfaces, which corresponds to the conceptual model hierarchy. For practical aid in interface design, further detailed functional analysis than have been presented here is necessary. To aid this process, Lind's MFM method (Lind, 1999) and the Ecological Interface Design methodology (Burns & Hajdukiewicz, 2004; Vicente & Rasmussen, 1992) are useful tools. There is also a big step between identifying the type of information necessary and then to provide visualizations that effectively communicate this type of information to the operator. This requires ingenuity of the person performing the development work. In today's, off-the-shelve DCS and SCADA systems there are also considerable limitations in what is possible to visualize in terms of graphical components. This may unfortunately obstruct even the very best of ideas and solutions from reaching the operative reality.

7.3 The usability perspective on automation

The motive for using the concept of usability in the problem definition was to clarify the problem field and to separate the thesis work from the aspects considering the choice of level of automation. Seeing a shift in level of automation as the solution to, for example the out-of-the-loop problem means that the control function is reallocated to the human operator from time to time to keep the operator in the loop. The standpoint in this work is that the information from the automatic system has to be designed in a way that the operator can follow and understand how the control system and the technical process works, rather than changing the level of automation. This standpoint originates from the experience that in process industry applications, cost efficiency and technological advantages drives the introduction of automatic systems. In this domain, the level of automation will never be lowered unless there is a strong economical or safety related rationale. (Indirectly, safety related issues are however often also economical issues.) This thesis work therefore assumes that the level of automation is given, and that the control system interface has to be designed to provide adequate support to the operator. High levels of automation per se are not seen as the problem, but poor control system interfaces are. Modern control systems are mainly computer based and therefore the concept of usability is relevant.

7.4 Delimitations in the thesis

The main limitation to how the model has been presented is the deliberate exclusion of the fact that the operator as good as always acts as part of a team and an organisation. This delimitation was made to facilitate the explanation of the model, but that does not delimit the models use for analysing teamwork. In fact, there seem to be a shift towards seeing automatic systems as a team member (Klein et al., 2005; Skjerve & Skraaning Jr, 2004) which means that an elaboration of the model in its present form, as to also account for several team members, is not that far reached. This elaboration must however be put on the list of future work for now.

The model's main intended use is as a catalyst for reasoning around what types of information that is necessary to support operators in their daily work in complex and dynamical socio-technical systems. By avoiding technical details considering the model's possible areas of application (details that the intended users of the model probably know better than the author does anyway) and by providing simple and hopefully descriptive examples of its use and its background, the model has been made accessible to a wide range of professionals within the human factors engineering community.

The approach to explain the emergence of the causes (i.e. the problems described in section 3.2) of possible performance degradation (i.e. loss of control) by using dissonance between knowledge and reality (Figure 22) has some problematic sides to it that need to be discussed. As was described in section 6.1, the conceptual model is not intended to capture detailed mental models. The reason for this is that mental models are individual constructs that on a detailed level are likely to differ between different persons, which make them a poor basis for design. For example, using subject matter experts as informants to depict their model of reality can give useful information. But their views, and therefore also their models on a detailed level are likely to differ from expert to expert. Capturing someone else's model and describing your own image of it will also mean ending up with a 'model of a model' which adds subjectivity to the description. There is a general consent among human factors specialists and researchers that to achieve efficient control, a mental model that match the system to be controlled, is necessary. Therefore the mental model must be adapted (i.e. through learning) to the work domain. To force the operator to adapt may at first glance seem as a violation of the human-centred approach. There is however a difference between for example consumer products, where the product is adapted to fit the user, and safety critical complex systems such as nuclear power plants, where the technology is the driving factor. It should also be recognized that shaping an operator's mental model of a complex system, does not in any way reduce the importance of an adequate control system interface that is adapted to human prerequisites.

7.5 Generalisation

Problems regarding how to design control system interfaces to avoid automation-usability problem are not specific for the nuclear domain. As mentioned in the theoretical descriptions, similar problems exist within aviation and shipping. This types of problems seem to be generic and related to the use of control systems to control a process that is not properly reflected in the control system interface. It should be stressed that high usability alone is not a guarantee for adequate human-machine system performance. Paper III presents an example from the medical domain, where two dialysis machines were compared. The newer machine had a higher level of automation and also better usability (i.e. it was easier to perform the intended tasks due to automation). The older dialysis machine had poorer usability and the nurses had to learn the functions by heart. It was found that users of the new machine had worse preconditions for learning to be prepared for unexpected events. The nurses using the older machine had better preconditions to handle extraordinary events since they were forced to learn all machine functionality. This resembles the classical 'Ironies of automation' (Bainbridge, 1983), but in this case the users of the new machine never had the chance to acquire the required knowledge in the first place. In the study, the knowledge structures of the nurses were not elicited. It is however likely that if their mental models were to have been described in terms of the conceptual model, the nurses using the new machine would have their main knowledge on the *Task* and *Situation* level, but little substance on the *Process* and *Function* level. The nurses using the old machine were probably forced to develop their knowledge on all levels to be able to use the machine at all. By highlighting this example, it is made clear that the use of the conceptual model is possible irrespective of domain. Because of the general applicability of the model structure, it can be used for analysis of any complex and dynamical socio-technical system.

7.6 Research contribution

This thesis presents research contributions in two areas. The first contribution is increased knowledge regarding automation usability problems in control room environments. These problems are important to understand if high productivity and safety are to be maintained in domains where automatic systems are used. The second contribution is a proposal of a conceptual model that describes human-automation related problems in a single framework. The conceptual model is intended to be used in a human factors engineering context.

The main research contribution is the compilation of the means-ends hierarchy, the perception-action cycle as a control loop, performance influencing factors, and levels of automation into a single conceptual model, which can be used to describe human-machine systems. The conceptual model facilitates description of the connections between the elements in a human-machine system and the way information and actions are interrelated in different levels of interaction. This description makes it easier to understand what affects the relationship between humans and machines. An example of this relationship is the automation usability problems (out of the loop, loss of skills, miscalibrated trust) that have been described and explained in this thesis through use of the conceptual model.

Further, the model is possible to use as a mediating object to facilitate reasoning about mental models and how a mismatch between mental models and the real world can lead to operational problems. By using the model as a tool for analysis in the design process, problems due to mental model mismatch can be prevented.

8
Conclusions

This chapter describes the conclusions from the entire thesis.

This thesis presents a conceptual model that can be used for analysis of automation usability problems.

By compiling the means-ends hierarchy, the perception-action cycle as a control loop, performance influencing factors, and levels of automation into a single framework, a conceptual model that is suitable to explain automation usability problems was created. The conceptual model has been used for analysis of the out-of-the-loop, loss of skills and trust problems, by using both an analytical and an empirical approach. Thus, the aims of the thesis have been fulfilled.

The proposed conceptual model is intended to be used by human factors engineers working in industry. The industrial application is important to contribute to the design of safe and efficient human-machine systems, which was the overall purpose of the thesis. The conceptual model however needs further development before it is ready for industrial application.

The specific purpose of the thesis was to describe how automation usability problems emerge, and to suggest how a systemic description can be used for analysis of human-machine systems in nuclear power plant control rooms. This has been accomplished by applying the conceptual model on data from a nuclear power plant control room field study.

It has also been indicated that the model can be used for analysis of a broad range of human-machine systems. This is possible due to the systemic character and the general applicability of the abstraction hierarchy, which is the foundation of the model.

9
Further Work

In this chapter, suggestions for future investigation that have arisen are presented.

The most important part of the coming work is the empirical validation of the conceptual model. This must be done from a number of viewpoints:

- **Application by other users.** Analyses with the conceptual model have now been conducted primarily by the author and a small number of colleagues. Others must also apply the conceptual model in order to show that it is useful and that the results do not depend only on the author's knowledge. It is also important that the conceptual model can be examined and criticised by a wider range of users in order to achieve improvements in the future.

  In order for the model to be of use to human factors engineers and other subject matter experts that are involved in the analysis and design of human-machine systems, a description of how to use the model in practice is necessary. To do this, a procedure for model use can be helpful. This has not been a part of the thesis work, but some initial thoughts can still be given regarding such a procedure. The suggestions for the procedure presented have not been evaluated in any way, and just represent the author's thoughts on what such a procedure may look like.

  Two procedures are proposed. The first procedure is for analysis of an existing human-machine system, and the second for use of the model as an aid in the design process of new, non-existing human-machine systems. The conceptual model can be used as a part in each step of the procedure, but additional methods are necessary.

  Suggested procedure for analysis of an existing human-machine- system:
  1. Describe the work domain using the means-ends hierarchy
  2. Examine the tasks (manual and cognitive) that are performed in the human-machine system
  3. Assess existing levels of automation applied in the human-machine system, i.e. define the role of the operator and the automatic system respectively

  Point 1-3 will then indicate the demands on the operator
  4. Assess the operator(s) knowledge on the different levels of abstraction
  5. Compare demands with operator knowledge to see if a mismatch exists
  6. If a mismatch exists, consider suitable measures to achieve a match.

  Suggested procedure for aid in the design process of new human-machine systems:
  1. Define the means-ends hierarchy of the work domain
  2. Define the tasks and decisions that have to be performed at each level of abstraction
  3. Decide what level(s) of automation to apply
  4. Decide how the control system interface should be designed for different levels of abstraction considering the means-ends hierarchy, the tasks and decisions and the level of automation
  5. Define the operator knowledge needed with respect to the level of automation and the control system user interface applied

6. Develop training program to shape operator knowledge to meet the demands of the human-machine system

These two procedures have to be tested, evaluated, and adapted to assure that the procedure for using the conceptual model in practice is applicable.

- **Model improvement.** The conceptual model has to this date been changed, restructured and updated numerous times. This process is likely to continue also after this thesis has been printed. The conceptual model is not claimed to be complete, nor to be the one 'correct' approach to analysis. However, it is the intention and a goal that the conceptual model should be a useful tool for human factors engineers doing work in industry. To achieve this, the model has to be continuously improved in order to meet the demands of the intended users.

  Some specific areas of improvement have been identified:

  - The conceptual model has to be improved to also account for teamwork activities. This is important since all operator work that takes place in control rooms are performed as part of a team.

  - The description of levels of automation can be made more exact. The representation of the level of automation in the conceptual model made in the thesis was made on an approximation of how different functions are allocated. This is in line with the general application that is suggested. Nevertheless this description can be made more precise by defining the human-machine system in detail. This should be useful when the model is to be applied in detailed engineering work.

  - The use of performance indicating factors in the conceptual model should be elaborated. In its present form, the conceptual model only makes use of PIFs in the *Situation* level. Considering PIFs as disturbances from a control theoretic perspective, PIFs exists on all levels in the model. It should also be clarified how PIFs can be used to predict performance on other levels, i.e. how a PIF affect the other levels in the model structure.

  - The conceptual model's possible role in interface design ought to be explored. An interesting aspect is how the different levels of abstraction in the conceptual model can be reformulated as information demands. As was indicated in the discussion, the conceptual model partly overlaps methodologies for interface design such as Ecological Interface Design (EID). This methodology does however not include usability as an explicit part, more than as a method for interface evaluation. It would be valuable to explore how the conceptual model and EID are related, and might complement each other.

- **Increased generalisability – employment in other areas of application.** The conceptual model has to this point been employed primarily for analysis of nuclear power plant turbine operations. A further aim is to apply the conceptual model also to other areas to show that the conceptual model is generally applicable. Examples of interesting domains with an extensive use of automation are pulp & paper, aviation, and oil & refinery.

10

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