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Nordic nuclear safety research

NKS-179
ISBN 978-87-7893-245-7

Levels of Automation and User Control - Evaluation of a Turbine Automation Interface

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October 2008

Abstract

The study was performed during the annual operator training at the Studsvik nuclear power plant simulator facility in Nyköping, Sweden. The participating operators came from the Oskarshamn 3 nuclear power plant. In the study, seven nuclear power plant turbine operators were interviewed concerning their use of the automatic turbine system. A field study approach together with a heuristic usability evaluation was made to assess how the operators' are affected by use of automation in the control room setting. The purpose of the study was to examine how operator performance is affected by varying levels of automation in nuclear power plant turbine operation. The Automatic Turbine System (ATS) was evaluated to clarify how the ATS interface design supports the operators' work.

The results show that during manual control the operators experience loss of speed and accuracy in performing actions together with difficulty of dividing 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, the need of feedback increases which means that information presentation also becomes more important. The use of the semiautomatic, step-mode is often preferred 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 experience the presentation of the conditions that manage the automatic sequences as difficult to perceive

Key words

levels of automation, usability, control room

NKS-179
ISBN 978-87-7893-245-7

Electronic report, October 2008

The report can be obtained from
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- Evaluation of a Turbine Automation Interface

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Acknowledgements

This work has been financed by NKS (Nordic Nuclear Safety Research) and Chalmers University of Technology. Thank you to the operators at Oskarshamn 3 and instructors Krister Walldem and Ronny Andersson for their support.

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1 Introduction

1.1 Background

The use of automation technology in the process industries tends to steadily increase. This happen since automation technology offers efficiency and stable control at the same time as it make the control room operators' job easier in many ways. Together with the apparent advantages, automation also comes with a number of concerns that has to be taken into account. From a human factors perspective there are a number of problems that has been identified and need to be taken seriously, such as out of the loop performance, skill degradation and trust in automation (Wickens, 2000). It is a considerable challenge to design new systems that take advantage of the automation but at the same time accounts for the human prerequisites. In literature, solutions to the problems of automation are often described in general terms, which make it hard to draw benefit from theory when designing new systems. In this report we connect theoretical aspects to concrete factors in the studied context to clarify the origin of the automation problems that were found. Examples are also given on how the design of new human-automation interfaces can be improved.

The study was performed during the annual operator training at the Studsvik nuclear power plant (NPP) simulator facility in Nyköping, Sweden. The attending operators came from the Oskarshamn 3 NPP.

The study is a part of a PhD student project at Chalmers University of Technology, Göteborg, Sweden. The PhD student project as a whole concerns how automation problems be identified and how new forms of interface design can be used to address these problems.

1.2 Purpose and objectives

The purpose of the study was to examine how operator performance is affected by varying levels of automation in nuclear power plant turbine operation. The Automatic Turbine System (ATS) was evaluated to clarify how the design supports or hinders the operators' work.

The objective was to create guidelines for presentation of automatic system activities that support the operators' work.

The following research questions were posed for the study:

- How are the turbine operators affected by differing levels of automation during plant upset?
- How does the ATS design support or hinder the operators in their work in terms of monitoring and control?
- How can the ATS design be improved in new systems to support monitoring and control?

1.3 Limitations

The session was a part of the ordinary operator training schedule and not designed specifically for the study. This limited the possibility to design a specific task and vary the levels of automation while keeping other factors constant. Instead operator knowledge and experience were elicited through interviews addressing the issues of interest. The study focused on the turbine side of the plant since it is more similar across different NPPs.

2 Theory

2.1 Types and levels of automation

According to Parasuraman et al. (2000) there are four types of functions where automation can be applied:

- Information acquisition
- Information analysis
- Decision making and action selection
- Action implementation

Within each type of automation the whole span from low to high degree of automation can be used, i.e. from manual to completely automatic. Below the different types of automation are described.

<u>Acquisition automation:</u> - To perceive and register input	
Low level:	For example, strategies to mechanically move sensors to scan and observe (e.g. radar scanning in a predefined pattern)
Intermediate level:	For example, organisation of incoming information with predefined criteria and highlighting of important parts (i.e. prioritisation lists)
High level:	For example, filtering of information where certain parts are chosen and presented to the operator.
<u>Analysis automation:</u> - Involves cognitive functions such as working memory and inferential processes	
Low level:	For example, algorithms that predicts the future based on input data (i.e. trends presented in the control room)
Intermediate level:	For example, integration where several input variables are combined into a single value.
High level:	For example, information managers that summarise data and presents it to the operator.
<u>Decision automation:</u> - Includes choice of several decision alternatives. The automation can augment or replace human selection of decision options with machine decision making.	
Low level:	No assistance is given. The operator takes all decisions and actions.
Intermediate level:	The operator approves/disapproves a choice that the computer has made.
High level:	The computer decides everything ignoring the operator.
<u>Action automation:</u> - Execution of the chosen action.	
	Automation in this phase involves different levels of machine execution. Often in the sense that the human hand is replaced by a machine. The level corresponds to the relative amount of manual vs. automatic activities during a task.

Information acquisition and information analysis can work well using a high level of automation as long as the operator has access to the raw data (Parasuraman et al., 2000) This means that highlighting should be preferable compared to filtering of information. It is also vital that the operator is aware of the systems unreliability. If the operator is aware of the information's unreliability, attention will also be given the original data.

According to Sheridan (2000) dynamic tasks should be automated using dynamic automation. If expert systems choose and executes decisions in a dynamic environment, there is a risk that the operator can't withhold a sufficient overview of the system and information sources. This happen since the operator is not active in the evaluation of the information that leads to decisions (Parasuraman et al., 2000). A high level of automation in decision making and choice of action can be justified for tasks with high time pressure since the operator's reaction time can be too slow. It is however important that a high level of automation requires equally high level of feedback to compensate for the operator's lack of involvement in the action execution (Parasuraman & Riley, 1997). Operators also tend to be less aware of changes in the environment or the technical system if the changes are implemented by someone else (another operator or automation) than if the operator himself should have implemented the change (Parasuraman et al., 2000). This is important to consider to avoid out of the loop problems.

2.2 Automation effects on human cognition and performance

A number of effects arise when automation is introduced. Three of the most commonly mentioned are out-of-the-loop problems, skill degradation and trust in automation.

2.2.1 Out-of-the-loop unfamiliarity

Out-of-the-loop performance problems are characterised by how humans find it difficult to detect automation failures and revert to manual control (Lee, 2006). This depends upon a number of factors. One is that automation may reduce feedback from the process. The feedback that exists is also different from when using manual control. Another factor is that automation puts the operator in passive observation of the process which puts higher demands on operator vigilance. Automatic control also means that the operator can engage and focus on other activities which make it even harder for the operator to observe all process feedback. Another cause for out-of-the-loop problems is that the operator has an inadequate mental model which gives false expectations. Altogether, the origin of out-of-the-loop unfamiliarity comes from disrupted feedback that reduces situation awareness which may provide false expectations and make shift to manual control difficult.

2.2.2 Skill degradation

Skill degradation refers to how operators tend to loose knowledge and skills in highly automated processes (Lee, 2006). The skill of performing tasks that previously were performed manually risk to diminish while the tasks are performed manually very seldom. This increases the demands on adequate training and effective procedures to avoid problems in case of an automation failure. Automation can also change the nature of work when manual actions are replaced by automation. When simple physical tasks are replaced by automation and the difficult tasks that are too hard to automate are left to human operators, the cognitive load tends to increase. Automation also makes it possible to handle more tasks simultaneously, which further increase cognitive load.

2.2.3 Trust in automation

Operators' trust in automatic systems affects how and if automatic functions are used. (Lee, 2006). 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 are lost. Over-trust on the other hand, occurs when the automation is believed to be more reliable than it actually is. This can cause the operator to fail in noticing when the automation not performs as it should.

2.3 Cognitive systems engineering framework

Understanding of the human role in a control room setting is central to be able to propose new design solutions that effectively support the operator work. The field of Cognitive Systems Engineering (CSE) takes the concept of man-machine interaction further and puts it in a system perspective. This is important while operator work to a large extent is distributed across the control room team, technology and work organization. Rather than focusing on the operators' internal processes, such as the human information process, CSE focuses on observable performance and what the system at hand actually achieves. These systems are referred to as Joint Cognitive Systems (JCS) and are characterised by how humans and artefacts adapt and manage to stay in control despite the influence from a context changing over time.

3 Method

3.1 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, see figure 1. (KSU, 2005). In this study the superior automation with its human-machine interface is the main focus. 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 main control room. The automatic sequences give start and stop orders to the functional group automation and individual objects.

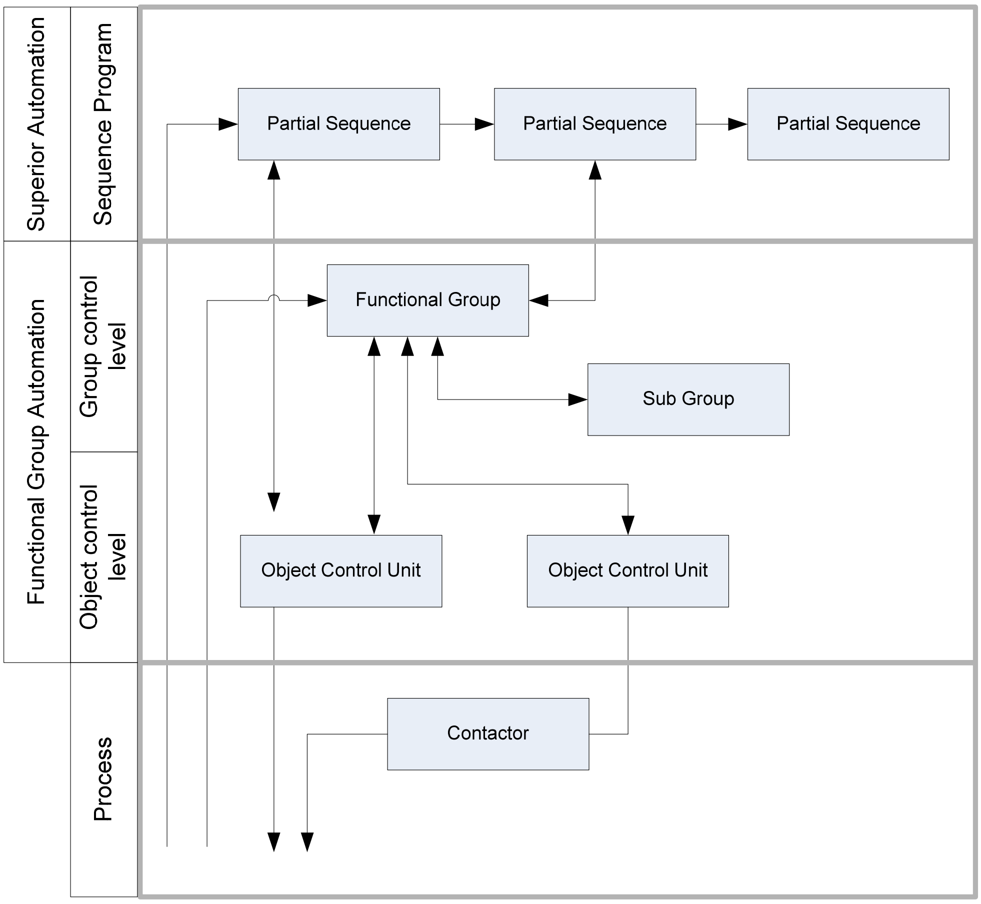

Figure 1. The ATS control hierarchy (Adopted from KSU, 2005)

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. 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 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.

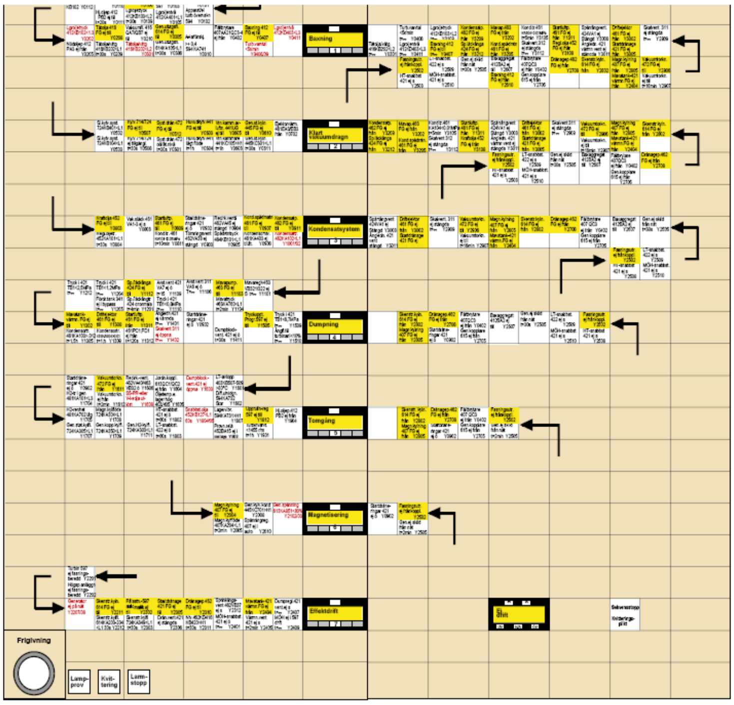

Figure 2. The ATS-interface, (Adopted from KSU, 2005)

In the ATS-interface the superior automation’s sequences are presented, see figure 2. 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 up an 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 lets the process stay at the highest stable state possible.

With the massive 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 shut-down step by step.

3.2 Methods

To assess the operator-ATS interaction a qualitative approach was chosen. This was done to identify possible problems and to elicit the turbine operators' view of their work with the ATS. Due to the prerequisites at the simulator training sessions, no quantitative measurements could be performed.

In the study seven nuclear power plant turbine operators was interviewed concerning their use of the Automatic Turbine System (ATS) at the Swedish Oskarshamn 3 (O3) nuclear power plant. The study was performed during the annual operator training at the Studsvik training facility in Nyköping, Sweden. Five shifts (approximately 20 persons) were observed during the simulator training. Of these operators a total of seven turbine operators from four shift teams were interviewed after the training sessions. The operators' level of experience differed from being under education to become licensed turbine operators to more than twenty years of experience. In every shift and during the interview sessions at least one of the turbine operators had more than two years of operative experience.

The nuclear power plant control room setting with the ATS offers a possibility to study the use of an automatic system with a challenging complexity. The Oskarshamn 3 power plant was chosen due to practical reasons while the plant management together with the operators welcomed the study and their training schedule matched the project planning.

3.2.1 Field study

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 field study approach was chosen while it allows a realistic view of the work setting. It also allows observation of how the distributed cognitive system adapts to upcoming events (Mumaw et al., 2000).

The operator crews conducted two eight hour long training shifts during two days at the training facility. These shifts were divided into different parts where the studied simulator session was one component. The simulator session lasted for approximately three hours and included handling of the ATS.

3.2.2 Interviews

The interviews were performed after the simulator sessions using a semi-structured methodology. The specific questions were posed to the operators and follow-up questions were asked and discussions followed. The questions were focused on the use of the ATS and how varying levels of automation affects the operators work. All questions used the recently performed training session with the tasks performed using the ATS-interface as a starting point. The operators were then asked how they would have been affected by changes in the level of automation in the specific situation. This was followed by an individual description of difficulties and situations the operators encounter using the ATS, and the discussions treated how the artefact design supports operator work.

3.2.3 Observations

The simulator sessions were video recorded using two cameras and several microphones mounted in the control room. One camera view gave an overview image of the control room while the other was fixed on the ATS control panel.

3.2.4 Interface evaluation using usability heuristics

The interview results pointed out a number of typical automation related problems (see section 5.1). The interview results also showed a number of difficulties in handling the ATS that are related to usability issues. While these difficulties in handling were found a heuristic usability evaluation was made. The inspection method uses a set of heuristics to systematically find usability problems in an interface. The heuristics were used to define the problems found through the operator interviews.

Jordan (1998) describes a set of ten principles that affect the usability of a product. In the studied context these are present in the operator-ATS interactions. Below follows a short description of each heuristic used in the usability evaluation.

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.

3.2.5 Guidelines to achieve joint cognitive systems that work

In the joint cognitive systems framework two concepts are of importance when designing technical systems; observability and directability (Christoffersen & Woods, 2002). Observability refers to the ability to see and follow what the automatic system does over time. Coagency between humans and technology requires that the different parts in the joint system can see what the others are doing. When automatic system actions happen without insight to what is going on we will get a black box which leads to automation surprises (Christoffersen & Woods, 2002). Further, just the availability of data does not automatically mean that the operator has access to meaningful information. How data is presented and related to operator work is of great importance. Directability refers to the possibility of using automation as an aid for control, also during deviations, rather than the operator taking over the control and performing it manually. Manual control means that all the strengths of the automatic system are lost, rather than trying to achieve cooperation and use the automation as a helping hand. A number of guidelines to achieve JCS that work are presented by Woods and Hollnagel (2006). These guidelines are presented and used in chapter 4.3 "*Analysis using cognitive engineering heuristics*" to analyse the studied work situation at O3.

3.3 Description of the Studsvik O3 Simulator Setting

The O3 simulator facility at KSU Studsvik consists of a full scope simulator with an instructor cabin, from where the training sessions can be controlled. The instructors also play the roles of maintenance personnel, management and other contacts that the operators have to take by telephone during the training session. The training program in general is adapted to handling of predefined anomalies so that the operators have to practice using certain procedures. The instructors judge the operators behaviour from their extensive experience and from a number of guidelines. These guidelines include the monitoring behaviour, control panel handling, communication behaviour, team work & leadership and procedure handling. After the simulator session the instructors go through and discuss the session with the participants.

3.3.1 Participants

The operator crews at O3 consists of one shift supervisor, one reactor operator, one turbine operator, assisting operator(s) and maintenance personnel. During the simulator sessions operators under education to become turbine operators also attended the training. The majority of the operators are male. In the study seven operators were interviewed using four interview sessions. The operative experience of the participants varied from 2 years to 20+ years. In the interview sessions at least one of the respondents were experienced.

3.3.2 The studied simulator session

The simulator session consisted of a series of anomalies for the operators to handle. A number of events cause the operators to engage in trouble-shooting activities, using different procedures. The time to complete the session varied between two to three hours. During these events the turbine operators use the ATS-interface two times performing actions connected to the automatic turbine system.

4 Results

The results are presented using operator comments that highlight problem areas of interest within each mode of operation. This is followed by a number of usability issues that connects to the automation problems identified. Finally, the results are analysed using the theoretical basis described in chapter two.

4.1 Levels of automation in the automatic turbine system

The control of the ATS can be described using three different levels of automation; manual-, step- and automatic mode. In all three modes the types of automation; information acquisition, information analysis and decision making & action selection have basically the same level of automation respectively. The greatest difference lies in action execution where the operator in manual mode uses the M/I-units on the control room panels, in step-mode uses the ATS step function and in automatic mode lets the ATS perform longer sequences of actions.

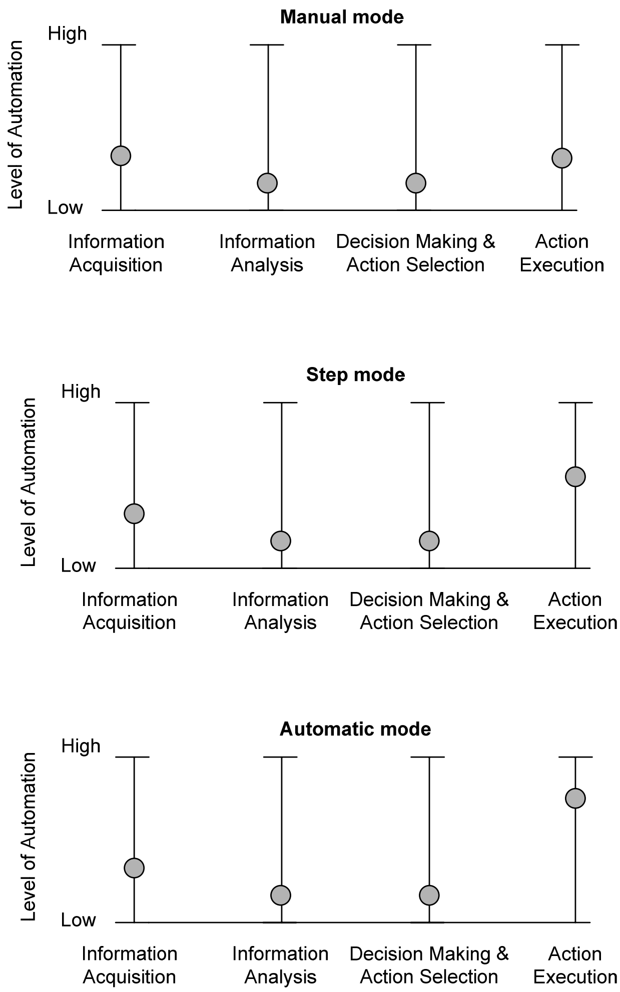

Figure 3. Levels of Automation in the different modes of operation

4.2 Interview results

The operators' comments 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.

- Manual mode
    - Easier to follow process
    - Strong focus on task / poorer over-all monitoring
    - Increased probability of human error
    - Increased feeling of control
    - Facilitates trouble shooting

- Step mode
    - Useful combination of good control and speed

- Automatic mode
    - Risk of loosing track in procedures
    - Trouble shooting becomes more difficult in automatic mode
    - Difficult to know what objects that are effected when engaging a sequence

- Usability issues
    - Low interface transparency
    - Inconsistencies with use of other systems

The ATS-interface is designed to guide the operator through the start-up and shut down procedures. While planned start-up and shut down of the plant is performed only once a year during outage, the operators has to rely to a large extent on the simulator training occasions to practice the handling of the ATS. Since the operative personnel consist of seven shifts, there is a possibility that a turbine operator won't handle the ATS in live situations for years. The M/I-units on other control room panels are however used more often in the daily operations.

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. This mode also involve the automatic reserve start function since the object control include automatic monitoring and start of redundant objects in case of failure. 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 as 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 isn't very long.

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.

4.2.2 The ATS in step mode

The turbine operator can also choose to manoeuvre the ATS in step-mode. In step-mode the ATS performs the program sequences only on push-button orders from the turbine operator. This gives the operator a possibility to control the ATS sequence by sequence and make use of the automations advantage of speed and accuracy.

When using the step mode the operator orders the ATS to the desired states using the ATS-interface. The step mode combine the speed of the automatic system with the possibility to check that process parameters has reach their desired values, and it gives the operator time to think in between the action sequences. According to the operators this combines feeling of control with the ATS speed and accuracy. The step-mode facilitates the achievement of common ground between the operator and the ATS, while the operator has time to perceive the position of the ATS, check the process status and prepare the next program sequence (project events in the near future). In this way the operator receives increased possibilities to support all three levels of situation awareness; perception, understanding and projection of future events. The projection of future events in this mode relies on following operating procedures which is regarded as the optimal course to proceed.

4.2.3 The ATS in automatic mode

In automatic mode 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 when the process fails to execute program orders. Feedback on what sequences that have been accomplished is continuously displayed in the ATS-interface.

"There is a risk that the automatic sequences run away from you, and you loose 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 gives the operator the possibility to check that the performed action has done 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's supposed to. The operators also review procedures before implementing an action, this way they have the expected outcome of the sequence to be engaged 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 increase 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 engage in the control. This gives 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.

4.2.4 How the ATS support operator work

During the interviews, deficiencies in the ATS-design were discussed. These results relate more to usability issues than to levels of automation and are therefore presented separately. 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) they can't see 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 engaged to reach a certain 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 impact the time to get the power plant back on to the grid again, and therefore has direct economical aspects. This problem tend to get worse as the level of automation get 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 the operators’ ability to match the object to their mental model of the plant would probably be improved.

“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 they, when handling the ÖA-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 ÖA-panel 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 ÖA-actions while all parts that affect the operation are not 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 ÖA-interface. These layers are highly linked but can’t 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.

4.3 Analysis using cognitive engineering heuristics

From the analysis of the interview results problems related to user interface design can be found as well as typical automation inflicted out-of-the-loop problems. Interface design and automation problems are tightly connected and not always separable. For example, the operators' difficulty of knowing what objects an automatic sequence influence in the process is connected to visual clarity in the interface and ease of relating the ATS-interface representation to objects in the process.

Woods and Hollnagel (2006) discuss how to meet requirements to support monitoring tasks in highly automated environments. The guidelines they provide address the importance of observability to improve feedback that provides insight into a process. An example of these generic guidelines is to;

- Align data to reveal patterns and relationships in a process
- Provide context around details of interest
- See sequence and evolution over time

To "*align data to reveal patterns and relationships in a process*" connect directly to the turbine operators' difficulty to see the relationships between the ÖA-interface items and affected objects in the process. To improve the visibility of the process relationships a graphical representation of the automatic sequences would probably be helpful. In the present control room, the process mimics on the wall panels functions as an enhancement of the operators' mental model of the plant that provides feedback from the process. A similar computer based mimic display that integrates the automatic sequences and clarifies what objects that are affected might function as a support for improved perception of relationships.

The "*provide context around details of interest*" guideline is important with respect to the difficulty of understanding and foreseeing the impact of conditions displayed in the ATS-interface. The conditions' impact is described in a separate document called the Sequence Program Matrix (SPM) (internal document available at KSU) where all conditions and program orders are listed. When studying the document it is evident that the document it is far from intuitive to interpret and draw conclusions regarding how a specific condition affects the process, even for an experienced operator. However, all this information is hardly necessary at all times and during normal operations. An improved presentation of the conditions relation and connections with the process will probably reduce the time for finding cause and effects during trouble-shooting activities to a great extent. The design of such a visual aid to make the connections visible will however not be a simple task while the interdependencies are complex.

The guideline "*see sequence and evolution over time*" is relevant while the ATS sequences follow the ATS-interface steps from axis standstill to effect operation on a straight timeline (during normal, problem free operation). An important time aspect is the condition time tolerance limits that state in what time a condition has to reach its desired state. Each condition has its own specific time range depending on the type of condition and what process it will engage. These time dependencies are visible through notations in the ATS-interface. The time tolerance is only annotated if it exceeds 20 seconds. The operators need to keep track of the amount of time that has passed since the condition was activated to know the time left to act upon. This can probably be done better in manual mode where the operator has full focus on the task at hand, but will become more difficult in automatic mode. A suggestion to improve the visibility of time dependencies would be to provide a timeline in the ÖA-interface where time tolerances are visible and parallel activities can be monitored more easily. This would also support the ability to follow the automatic sequences during normal operation.

4.4 Analysis using usability heuristics

The ATS interface has also been evaluated using usability heuristics (see section 3.2.4). The interview results pointed out that usability problems exist in parallel to automation inflicted problems. Below, each heuristic is followed by the issues that were found in the ATS.

Consistency

Problems with consistency between subsystems are probably the most common usability issue in complex systems. When artefacts require different ways of performing similar tasks it causes difficulties in keeping the handling consistent, increasing the probability of erroneous actions. Also similar tasks with differing restrictions can cause confusion. For example, the block computer event list is the natural place for the operators to look for information and feedback regarding what has happened in the process. However, all events in the ATS are not presented in the control room block computer event list. Especially, what the operators refer to as "disappearing conditions", cause confusion and the feeling of an opaque interface. The disappearing conditions are caused by conditions that blink and then disappear without notice when the condition has been fulfilled. Also in the "pants down" situation described in the results section consistency plays an important role. The operator is used to that unaccepted alarms do not cause any further problems, they are simply unaccepted. In the handling of the ATS the unaccepted condition here results in a turbine scram due to the condition causing the turbine program to go back to a lower steady state.

Compatibility

In the ATS interface the same M/I-control units are used as on the control room wall panels but in the ATS interface they are turned upside-down to make clear that the principles of indication of feedback values differs from the general principle. In the ATS interface, a stable state has to have all its conditions fulfilled to indicate that the ATS interface corresponds to the process feedback value.

Feedback

The ATS-interface is used as an indication of if the orders given have gone through. How these orders affect the process is however monitored on the wall panels, where process values are monitored. In this respect the ATS interface works as a hard wired procedure to follow during start-up and shutdown. The feedback given on how the ATS conditions affect the process is also considered to be poor by the operators. What orders that goes through or conditions causing a stoppage is controlled by the ATS's underlying logic. This is only accessible through logic schedules available in binders in the control room. Finding and diagnosing a anomaly using the logic schedules can be difficult and often very time consuming, making it difficult to quickly trouble-shoot an arisen problem.

Error prevention and recovery

There is a possibility to check what conditions that are monitored and what are fulfilled using a button on the ATS interface. This gives the operator a possibility to check in advance if the desired order will go through in step-mode. There is no possibility to recover an error in the ATS, in terms of "undoing" a performed action. Instead the operator has to be supported in foreseeing what effects an action will have. Skilled operators has the process knowledge and experience to do this relatively unhindered. To avoid erroneous actions altogether, consistency is of importance so that similar actions will give similar effects.

User control
When using the ATS in automatic mode the operators mention the risk of the automatic sequences “running away” from them. The operators cope with this by using the step mode instead giving them increased control over the action sequences. The ATS speed in automatic mode is too high for the operators to, at the same time, follow the action sequence in the paper based procedures. The automation speed hereby makes the operators job to check procedures and stay updated on the process harder. Procedures that incorporated a perceptual, more efficient way of matching procedures with process response would probably be useful to the operator. This would facilitate operator work and perhaps also increase the use of the automatic mode.

Visual clarity and explicitness
In the ATS-interface a small font is used with abbreviations and numeric codes that gives a cluttered appearance. According to the operators the negated expressions (i.e. *“feedwater pump not on”* or *“phasing equipment not off”*) also cause a need to think twice. The negated expressions are used to achieve a black-board configuration with as few lights lit as possible, and there is a trade off between these two. On one hand the use of sometimes confusing negated expression and on the other hand the usefulness of the black-board configuration that make deviances more emergent when lamps are activated.

To improve the operators’ trouble-shooting abilities the functional relationships in the process should be better connected to the use of the ATS. The problem of knowing what objects that have been affected when engaging an automatic sequence and thereby knowing where to start looking for the failure would be facilitated by an improved interface. With the present equipment the operators has to rely on complex paper based logic schemes and experience of earlier failures. As mentioned above, the design of an improved interface with all connections and interdependencies visible is a considerable challenge. The utility of making all information visible is of course questionable, but giving the operators a jump-start in trouble shooting activities will certainly reduce the time needed to a great extent.

Prioritisation of functionality and information
During normal operation when the ATS is used for start-up and shutdown, the information given through the interface is sufficient to bring the plant to a desired state. When facing an anomaly the ATS interface has some deficiencies which are mentioned above. This is also reflected in the comments given by operators on how it would have been easier to engage in trouble-shooting activities if manual mode had been used in case of an automation failure.

4.5 Analysis of human-automation problems in the O3 setting

Several of the human-automation problems described in literature [(Dekker (2002), Hollnagel & Woods (2005), Lee (2006), Parasuraman et al. (2000), Woods & Hollnagel (2006)] have also been found among the operators in the control room at O3. The interviews show that the operators are aware of these problems and cope with them through caution and reflection before interacting with the ATS. Anyhow, mistakes has happened that point out issues in the interface design that should be addressed.

4.5.1 Out-of-the-loop syndrome

To handle anomalies in the ATS is difficult according to the operators. To find the root cause of a failure can be very time consuming, and trouble-shooting activities would have been easier if the actions preceding the anomaly had been performed manually. The cause for this is most likely the difference in feedback from the ATS panel, compared to performing actions manually. The feedback cues in manual mode are both visual and proprioceptive, while automatic mode gives only visual feedback that provides poor assistance in deviating situations. In manual mode the operator’s attention is also specifically directed on the task at hand which improves awareness of actions and feedback. This can, to some extent, explain the out-of-the-loop experience when engaging in trouble-shooting activity.

4.5.2 Skill degradation

The ATS is used seldom in normal operations. Without anomalies the equipment is used during outage and training, leaving only a few occasions per year for hands on practice. Due to the shift work the operators may however not use the equipment in normal operations for years. The training sessions provides valuable occasions to maintain knowledge and skill, yet the training only takes place once a year leaving a feeling of insecurity when having to perform critical actions in live situations. Under these circumstances there is a substantial risk for skill degradation where the simulator training becomes very important to maintain the practical skills.

4.5.3 Trust in automation

The operators’ general comments regarding trust are that the ATS is reliable and that the ATS fails very seldom in the real control room setting at O3. To judge whether over-trust occur was however difficult. Comments that the ATS is perceived as “tricky” can still be argued to neutralize over-trust, since the operators are aware of the ATS underlying complexity. This was however mentioned by too few operators to give any certainty. In the simulator setting the situation was the opposite while the training to a large extent is based on trouble shooting different anomalies, where the ATS is supposed to fail. To what extent this affected the operator comments on trust is also difficult to say.

4.6 Summary of strengths and weaknesses in the ATS

During manual control the operators mention loss of speed and accuracy in performing actions and difficulty 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 mention the presentation of the conditions that manage the automatic sequences as difficult to perceive. This has also caused costly errors due to presentation problems and inconsistencies compared with the handling of other systems in the control room.

5 Discussion

5.1 Results

The main finding of how the operators need more guidance in case of a failure in automatic mode points out the need of interfaces where the operator can follow the process. It is also necessary that the operator can get information on what has happened. The event list now provides this function, but the list format in its present form is not a tool that is sharp enough. Since digital presentation is used in newer systems one can question utility of the findings on a hard wired system. In modernization projects the old configuration is however often copied and used in digital format. If the functionality is the similar, the comparison can still be of use.

The results are based on interviews with seven turbine operators. The small number of participants was limited by the number of available turbine operators and the possibility of attending the simulator training sessions. The study would benefit from a larger set of participants making the increasing the validity of the results. The interview results point out existing issues related to differences in the level of automation. To verify these results, when and how often they occur, more research is needed using specific simulated tasks where other factors than the change in level of automation can be held constant.

The turbine automation supports the operator by facilitating the performance of actions to bring the turbine system to a desired state. The workload is hereby reduced to a great extent compared to manual operations. The usability problems that were found can be resolved by thoughtful interface design improvements that take usability guidelines and the operators needs and prerequisites into account. It is also important to use a systemic approach where the ATS is seen as a part in a larger system to avoid problems with inconsistency.

5.2 Method

A weakness of the field study methodology is that the researcher has limited control over the studied setting, which means that the researcher can’t prove full understanding of the studied phenomenon (Dekker, 2002). In field studies it can’t be concluded that the observed events represents a significant part of the variance of what is studied. Field studies are however useful to discover and confirm that a certain phenomenon takes place, see what factors of influence that exist and to find patterns for the problem of interest. In this respect the results has proven the usefulness of field study as method.

In the study, the interviews took place after an eight hour simulator session. Asking participants to recall subjects of interest from memory introduce an uncertainty in whether they recall their memories correctly. The participants will also “tell their story” as they perceived it, adding subjectivity. Increasing the number of participants would increase the validity, but the number of turbine operators available is however limited.

Since this study was made in hybrid control room with relatively old technology, one can question whether the results are valid for newer control room environments. Newer technology is often better and has addressed problems in older versions. An easy way to go when developing new screen based interfaces is to make a solution similar to the previous hard wired version. This has advantages in making the user adopt the new technology quickly and proving the systems functionality. The negative side is the loss of the potential the new technology (i.e. screen based graphics) can give. In the nuclear industry where demands on nuclear power companies and system vendors to prove safety are immense, the possibility to draw full benefit from new technology can be difficult.

The choice to use heuristic evaluation as method helped defining the problems that were found in the ATS interface in an effective way, but since it was done only by one person it does not find all possible usability issues. The study also shows how usability problems connect to and worsen classical automation problems. In literature, usability is however seldom mentioned when discussing automation problems such as out of the loop symptoms, trust and loss of skills. In all interaction with artefacts, usability is important to ensure understanding and ease of use. When considering usability issues the interaction is often limited to user and artefact and how the user perceives the artefact's interface. In the case of usability of automatic systems the usability perspective becomes even more important while the operator can delegate tasks to the automatic system. The user needs to understand the artefact interface and be able to follow what the autonomous functions are doing to avoid automation related problems.

The guidelines and heuristics used when evaluating the ATS can also be used to avoid automation problems in future design.

6 Conclusions

The following conclusions could be drawn from the results of the study:

The use of field study and interviews as a tool for eliciting information about how operators are affected by use of automation proved useful. To perform the study in connection to simulator training facilitated the operators’ ability to connect the questions to real situations and passed events. A disadvantage is however the laborious and time consuming process of analysing verbal data.

How are the turbine operators affected by differing levels of automation?
Manual mode gives the operators the ability to maintain control as they perform actions by hand. This feeling of control comes at the cost of the speed and accuracy of the automation.

The step-mode is the level of automation the operators prefer most of the time. This is due to the ability step-mode give to both stay in control while at the same time utilize the ATS speed and accuracy.

In full automation the operators can take advantage of the speed and accuracy of the ATS, but at the cost of control and increased difficulties in handling deviances due to poor observability of the ATS automatic actions.

If an anomaly occurs in the ATS after all, it would have been easier to trouble-shoot if manual operation had been used, due to the operator being in the loop and having had attention on the course of events. This finding indicates that the information presented in the ATS interface gives little support in case of failure.

How does the ATS design support / hinder the operators in their work in terms of monitoring and control?
The ATS supports the operator through its sequential design making it possible to foresee the effects of actions that are to be implemented. Problems with observability of the automatic systems´ underlying program and presentation of conditions were noted. Usability issues with inconsistency and error recovery was also found affecting the ATS operation.

How can the ATS design be improved in new systems to support monitoring and control?
By increasing the observability of conditions and underlying program logic it would be possible to reduce the problems identified. There are several design challenges that have to be addressed since a simple interface stands in contradiction to the complex interdependencies that have to be presented. More research and experiments with different forms of presentation must be performed to find a suitable solution. The improvement of the operators’ ability to take over control when shifting from automatic to manual mode in case of a failure depends heavily on providing relevant information on the ATS status. The possibility to follow the ATS actions during automatic operation is important to maintain the operator in the loop and to facilitate trouble shooting in case of an ATS failure.

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Title	Levels of Automation and User Control - Evaluation of a Turbine Automation Interface
Author(s)	Jonas Andersson
Affiliation(s)	Chalmers University of Technology, Sweden
ISBN	978-87-7893-245-7
Date	October 2008
Project	NKS-R / AutoNewTech
No. of pages	27
No. of tables	1
No. of illustrations	3
No. of references	14

Abstract

The study was performed during the annual operator training at the Studsvik nuclear power plant simulator facility in Nyköping, Sweden. The participating operators came from the Oskarshamn 3 nuclear power plant. In the study, seven nuclear power plant turbine operators were interviewed concerning their use of the automatic turbine system. A field study approach together with a heuristic usability evaluation was made to assess how the operators' are affected by use of automation in the control room setting. The purpose of the study was to examine how operator performance is affected by varying levels of automation in nuclear power plant turbine operation. The Automatic Turbine System (ATS) was evaluated to clarify how the ATS interface design supports the operators' work.

The results show that during manual control the operators experience loss of speed and accuracy in performing actions together with difficulty of dividing 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, the need of feedback increases which means that information presentation also becomes more important. The use of the semiautomatic, step-mode is often preferred 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 experience the presentation of the conditions that manage the automatic sequences as difficult to perceive

Key words levels of automation, usability, control room

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