Nordisk kernesikkerhedsforskning
Norrænar kjarnöryggisrannsóknir
Pohjoismainen ydinturvallisuustutkimus
Nordisk kjernesikkerhetsforskning
Nordisk kärnsäkerhetsforskning
Nordic nuclear safety research

NKS-237
ISBN 978-87-7893-309-6

Automation strategies in five domains – A comparison of levels of automation, function allocation and visualisation of automatic functions

Jonas Andersson

Chalmers University of Technology, Sweden

January 2011

Abstract

This study was conducted as a field study were control room operators and engineers from the refinery, heat & power, aviation, shipping and nuclear domain were interviewed regarding use of automation and the visualisation of automatic functions. The purpose of the study was to collect experiences and best practices from the five studied domains on levels of automation, function allocation and visualisation of automatic functions. In total, nine different control room settings were visited. The studied settings were compared using a systemic approach based on a human-machine systems model.

The results show that the “left over principle” is still the most common applied approach for function allocation but in high risk settings the decision whether to automate or not is more carefully considered. Regarding the visualisation of automatic functions, it was found that as long as each display type (process based, functional oriented, situation oriented and task based) are applied so that they correspond to the same level of abstraction as the technical system the operator’s mental model will be supported. No single display type can however readily match all levels of abstraction at the same time – all display types are still needed and serve different purposes.

Key words

control room, automation, function allocation, visualisation

NKS-237
ISBN 978-87-7893-309-6

Electronic report, January 2011

NKS Secretariat
NKS-776
P.O. Box 49
DK - 4000 Roskilde, Denmark

Phone +45 4677 4045
Fax +45 4677 4046
www.nks.org
e-mail nks@nks.org

Automation strategies in five domains

– A comparison of levels of automation, function allocation and visualisation of automatic functions

Jonas Andersson, Anna Lisa Osvalder

Division Design & Human factors
Department of Product and Production Development
Chalmers University of Technology
SE-412 96 GÖTEBORG, Sweden
E-mail: jonas.andersson@chalmers.se

Abstract

This study was conducted as a field study were control room operators and engineers from the refinery, heat & power, aviation, shipping and nuclear domain were interviewed regarding use of automation and the visualisation of automatic functions. The purpose of the study was to collect experiences and best practices from the five studied domains on levels of automation, function allocation and visualisation of automatic functions. In total, nine different control room settings were visited. The studied settings were compared using a systemic approach based on a human-machine systems model.

The results show that the "left over principle" is still the most common applied approach for function allocation but in high risk settings the decision whether to automate or not is more carefully considered. Regarding the visualisation of automatic functions, it was found that as long as each display type (process based, functional oriented, situation oriented and task based) are applied so that they correspond to the same level of abstraction as the technical system the operator's mental model will be supported. No single display type can however readily match all levels of abstraction at the same time – all display types are still needed and serve different purposes.

Acknowledgements

This research project has been financed by NKS (Nordic Nuclear Safety Research) and Chalmers University of Technology, Division Design & Human Factors. Thanks are due to the all the participants; operators, engineers and other interviewees for their time and patience.

Table of contents

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. Automation often gives economical benefits due to the reduction of personnel and facilitation of effective production. It also has the potential to improve safety where human abilities are insufficient. However, automation also comes with a number of concerns that has to be taken into account. From a human centred perspective there are a number of problems that have been identified and need to be taken seriously to achieve safe, reliable and effective automation. Examples are out of the loop performance problems, skill degradation and trust in automatic system (Wickens & Hollands, 1999). The frequent occurrence of these problems show that it is a considerable challenge to design new technical systems that take advantage of the benefits of automation but at the same time accounts for the human prerequisites.

1.2 Purpose and objectives

The purpose of the project is to collect experience and best practises from the refinery, heat & power, aviation, maritime and nuclear power domains, regarding digital control room solutions. A special focus is made on levels of automation, function allocation and visualisation of automatic system functions.

The following research questions were posed for the study:
How do different industries try to achieve optimal level of automation?
How do different industries allocate tasks and functions?
What differences and similarities regarding visualisation of automatic functions can be found across safety critical domains?
How well do these visualisations support the tasks and situations that operators deal with?

1.3 Limitations

The project was limited to study five domains. Several other domains, where control room environments are present, are potentially interesting but could not be included due to time and financial limitations.

2 Theory

2.1 Human-automation interaction from a systems perspective

Figure 1 describes a human-machine system model that is useful to describe the relationship between humans and automation. The control room operator controls a physical process either by acting directly upon the physical system or by using a control system. The physical process reacts on the operator's actions and sends information about the process status back to the operator, directly or via the control system interface. The environment also affects the human-machine system in several ways. The physical process is, for example, constrained by the physical laws, humans are in turn constrained by behaviour and cognitive abilities. The goals of the system are achieved by the operator when controlling the physical process with aid from the control system. The model in figure 1 is used to describe the domains that are compared in this study.

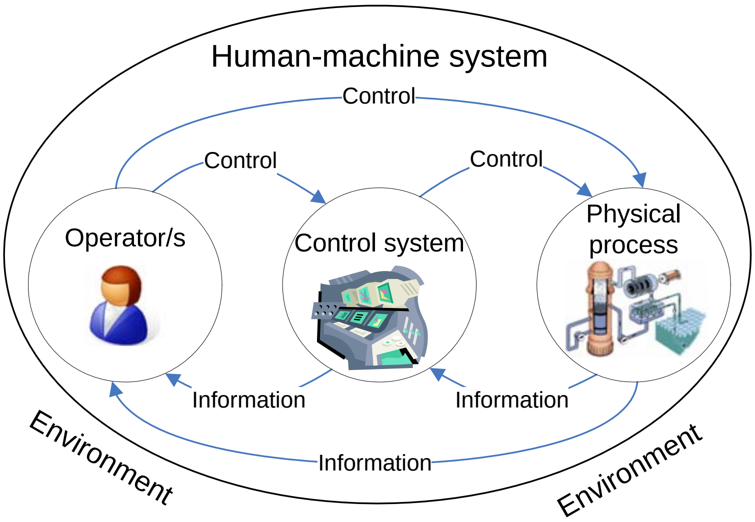

Figure 1. Human-machine system model

One of the effects of increasing use of automation is the change of operator roles from manual work to supervisory control. Tasks that previously were performed manually are now performed by the automatic system that is supervised by a human operator. This change causes new challenges to the operator. When tasks were performed manually the operator could more easily focus on one task at a time, using both physical and cognitive resources. With increasing use of automation several tasks are monitored simultaneously without need to intervene, inflicting higher cognitive demands and risks for various problems such as skill degradation, complacency, out of the loop problems and trust in automation. There is however no doubt that automation has improved the process- and energy industries to a great extent, with better means for effective and precise control. The question is rather how automation technology can be used in a balanced way to avoid problems and maximise the benefit from technology in a safe way with respect to human abilities.

2.2 Types and levels of automation & function allocation

According to Parasuraman et al. (2000) there are four types of functions where automation can be applied: information acquisition, information analysis, decision making & action selection and 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. The different types of automation are described in table 1.

Table 1. Types and levels of automation

Acquisition automation: - 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.
Analysis automation: - 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.
Decision automation: - 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.
Action automation: - 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.

Figure 2 describes how automation effectiveness decreases as a result of human factors related automation problems. All of these problems (out of the loop unfamiliarity, loss of skills, deficient calibration of trust, situation awareness problems, behaviour adaptation and so forth (Lee, 2006)) contribute to the loss of effectiveness above a certain level of automation. Where the curve starts to bend depends on the interplay of several factors; the domain characteristics and external factors, task difficulty, how well the control system can display information and the operators' ability to interpret the information to avoid problems. Team work and organizational factors also influence the overall performance.

In figure 2, point "A" describes how effective the work system is without automation, when all tasks are performed manually. The incentive to automate a task depends on how much you can gain on doing so. This gain is affected by how difficult a task is to automate or how complex the task is. The higher point "A" lies on the Y-axis, the less the operator will lose on abandoning use of automation in terms of effectiveness. Point "B" represents the highest effectiveness that can be achieved, before performance starts to drop.

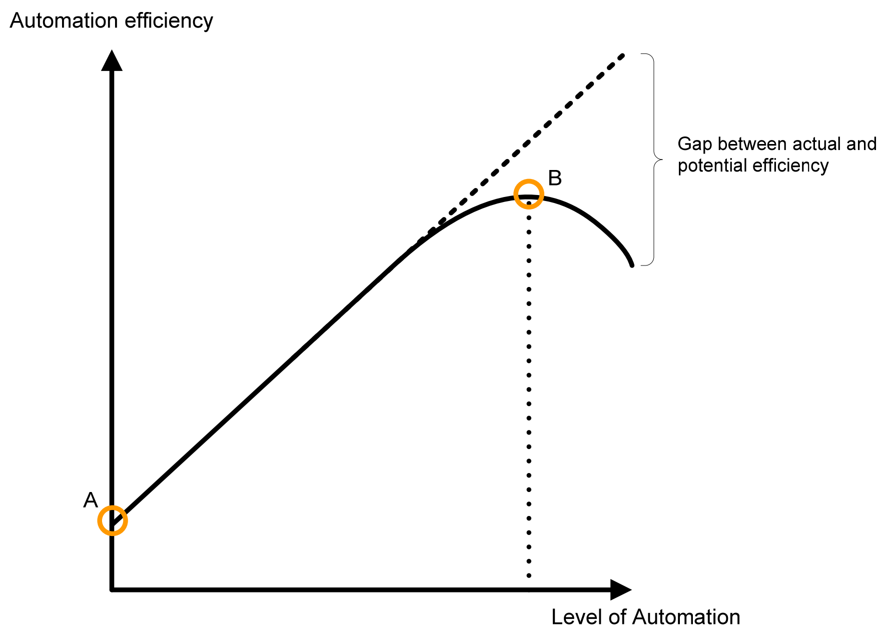

Figure 2. Adapted from (Frohm, 2008)

By avoiding automation problems the work system can get closer to its potential efficiency which is represented by the dotted line.

The more dynamic and complex a task is, the more difficult it becomes to automate it. The automated task must be relatively stable in the required performance to achieve cost efficient automation. This means that human operators often perform complex and dynamic tasks and easy tasks are automated.

In literature, three principles of function allocation (i.e. choosing what level of automation to implement) are mentioned as the most common ones; left-over-, compensatory- and the complementary principle (Hollnagel & Woods, 2005).

To achieve a well balanced work system the complementary principle offers an alternative to the left-over and compensatory approaches. Balance is achieved between performance resources and production demands such as safety and efficiency. Here, the demands consists of avoiding problems caused by automation, such as described in section 2.4.

The complementary principle states that functions in a socio-technical system should be distributed with regards taken to the work system as a whole. Tasks should not be allocated to either the human or the machine, but instead tasks should be designed so that the interaction between the human and the machine allows them to complement each other in reaching the desired goal. To achieve this, it is necessary to apply a development process that takes human aspects into account from the start. When human factors issues have to be accounted for in hindsight, it is often an expensive and laborious project to adapt and redesign technology and organisation to make the human-technical system safe and effective to use. A method for complementary function allocation is described in (Grote et al., 2000).

2.3 Visualisation of automatic functions

Christoffersen & Woods (2002) have identified two key characteristics of automation that have to be designed in from the beginning to achieve automation that fulfils the concept of cooperation, namely *observability* and *directability*. Users need to see what the automation is doing and what actions it will perform in the future. Observability is important so that an operator can detect when intervention is necessary, preferably before a critical state has been reached. Users also need to be able to direct activities when an intervention is necessary. Often this is done in an "all or nothing" mode using full automation or no automation at all. This means that in the case of abandoning automation, potentially useful functions of the technology are lost. By designing for observability and directability Christoffersen and Woods implies that cooperative automation can be achieved and unwanted automation effects can be avoided.

The time perspective is important when designing automation that support the operators understanding and ability to revert to manual operation in case of a failure (Hollnagel & Woods, 2005). Providing a picture of the past, the present and the future supports the operator in understanding what has happened, what is happening and what actions the automatic system is about to perform in the future. This is in line with theories on situation awareness and how to design for situation awareness (Endsley et al., 2003).

Five approaches has been identified that can be used to design visual displays in control room environments (Bligård et al., 2008):

Process oriented displays
The basis of a process oriented display is the physical process as described in for example technical flow charts and blue prints. The physical process is divided into process sub systems and each display show a sub system in varying degrees of detail.

Functional oriented displays
In functional oriented displays, a functional analysis is the basis for how to design the display content. A display can be dedicated to control and monitoring of a specific function, (e.g. "pumping of feed water"). All parts of the process affecting the operation of the displayed function are accounted for and their relation is depicted in the graphical display. In contrast to a process oriented display, the functional oriented approach means that parts lying physically far from each other, but are parts of the same function can be presented in the same display.

Task based displays
By using a task analysis as a starting point, action sequences are generated that in turn are used as basis for the display. This approach creates a display that supports the performance of a specific task in an efficient way. The display presents the controls necessary to perform the action sequence in the same order as they will be used. The approach is suitable for complicated tasks that include many sub steps.

Situation oriented displays
In a situation oriented display the design is made to support the handling of a specific operational situation. It has resemblance with the task based approach while a specific situation often demands for a certain set of action response. This approach requires that the situation is well known and easy to identify and that an established action or monitoring sequence exists to deal with the situation. All parameters and controls necessary to deal with the situation are then collected in the same display to facilitate handling of the situation.

Ecological displays
The basis of ecological interfaces is the abstraction/means-ends hierarchy (Rasmussen et al., 1994). Using the hierarchy as a basis, information relevant at different levels of abstraction is displayed in the interface. In the higher levels of abstraction, energy and flow balances are displayed and at the lower levels it is shown how subsystems and objects contribute to the overall system function. This approach facilitates the detection and handling of unexpected events. For examples see (Burns & Hajdukiewicz, 2004).

The display principles described above are often used in combination with each other. Generally, the process based principle is used to some extent in all displays since the physical layout is reflected in the display. Depending on the goal of the operators work, different principles can be used to support the operator's work in an effective way.

2.4 Automation effects on human cognition and performance

A number of effects arise when automation is introduced. Three of the most frequently occurring in this study were out-of-the-loop problems, skill degradation and trust in automation.

2.4.1 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.

2.4.2 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.

2.4.3 Trust in automation

Operators' trust in automatic systems affects how and if automatic functions are used (Lee & See, 2004). 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.

3 Methods

The methods used in the study are briefly described. Thorough descriptions can be found in the indicated references.

3.1.1 Field study

The study was conducted as a field study where several visits were made in the five chosen domains. Interviews were made with operators and persons responsible for control room modernization projects. The field study approach was used since it allows for a view of work taking place in its natural setting. Below is a list of the number of units visited and the number of operators and engineers interviewed in each domain.

Table 2. Visited units and number of respondents in each domain

Domain:	Refinery	Heat & power	Aviation	Maritime	Nuclear
Number of units visited	1	3	1	2	2
Operators interviewed	2	5	3	3	7
Engineers interviewed	2	3	1	1	1

The units were chosen on the combined criteria of being leaders in their domain in Sweden and being available for visits and interviews. The included companies were Refinery; PreemRaff Lysekil. Heat&power; Göteborg Energi / Sävenäs & Rya, Fortum / Hässelbyverket. Aviation; SAS Flight Academy. Maritime; Wallenius Wilhelmsen / m/v Fidelio, Stena Line / Stena Danica. Nuclear; OKG / O3 simulator, Ringhals R4.

3.1.2 Interviews

Interviews were performed with operators and persons responsible for control room modernization projects using a semi-structured approach. Questions were prepared beforehand and the respondents were encouraged to speak freely and add comments of interest.

3.1.3 Observations

Where it was possible, observations were made of how the operators used the automatic systems in real time operation. In the aviation and nuclear domain, simulator training sessions was attended. In cases where interaction with actual task performance was not possible, the interface was described using walk through without interaction.

3.1.4 Participants

The operators within each domain can be considered expert users of their individual systems. Generally, they have several years of experience and a thorough knowledge of how to perform their work tasks.

In the process industry domains (heat & power, refinery and nuclear) the shift teams are larger due to the size of the controlled process. The definition of roles and responsibilities are clearer in the safety critical domains.

3.1.5 Domain comparison

The generic system model presented in figure 1 has been used as a starting point to describe the different domains that are included in the study. Five domains were chosen for comparison; refinery, heat & power, aviation, maritime and the nuclear domain. The nuclear domain is included as a reference in the comparison. The main criteria for the choice of domains were high usage of automation in the controlled processes. Other domains such as oil&gas, ship bridges and air traffic control were considered but excluded due to project limitations.

To be able to analyze the use of automation in the studied domains, domain characteristics have been taken into consideration. Considering domain characteristics will facilitate the explanation to why a domain differs from another in terms of levels of automation, function allocation and presentation of automatic functions. The aim of the comparison is to give input to the nuclear domain on concepts and ideas regarding automation applications used in other domains. To perform a relevant comparison of domains that differs widely in both criticality and process character, a number of properties were chosen that are important in operation of the technical system. The properties are described below. The comparison of the properties was made relative to each other, which means that the rankings (high, average, low) presented in the results section are not absolute values. The categories are based on the human-machine system model (figure 1) presented in section 3.1.

1. Work description
   Brief description of what type of work that is being performed in the human-machine system.

2. System description
   - System goals (2a)
     Description of the goals of the entire system (operator, control system and physical process)
   - Physical process (2b)
     Description of the physical process and its inherent elements
   - Control system (2c)
     Description of the technology that controls the physical system
   - Operator (2d)
     Background, education and training
   - Organisation of physical process (2e)
     The types of inherent objects
   - Organisation of operators (2f)
     How the operators are organised when performing their work tasks
   - System environment (2g)
     How the system's surroundings affect the human-machine system

3. Physical process properties
   - Complexity
     Number of objects to monitor and control (3a)
     Coupling between objects (3b)
     Predictability in connections between objects (3c)
     Dependency between objects (3d)
     Influence from variations of external factors (3e)

- <u>Dynamics</u>
  Stability (ability to maintain structure) (3f)
  Rate of change of process variables (3g)

4. Control system properties
   - <u>Automation</u>
     Collection of data (4a)
     Analysis of data (4b)
     Decision making and selection of action (4c)
     Performance of actions (4d)

   - <u>Proximity</u>
     Proximity to physical process (4e)

   - <u>Measurement</u>
     Precision of measured data (4f)
     Speed from control actions to finished action (4g)
     Accuracy of the control system's action on the physical process (4h)

   - <u>Interaction</u>
     Amount of time the operator has to spend monitoring the control system (4i)

5. Operator properties
   Level of generic education (5a)
   Level of specialised education (5b)

6. Organisational properties
   Percentage of working time the operator performs monitoring tasks (other tasks can be planning, work outside of the control room etc.) (6a)
   Level of team work required to perform tasks (6b)
   Level of operator work rotation (6c)

7. Task characteristics
   Typical tasks that are relevant in each domain respectively

4 Results and analysis

In the results section the field study results are presented. First the comparison of domain characteristics is described. Secondly, the levels of automation used in each domain are described. After that the allocation of functions between human operator and automation is described, with emphasis on how balance is achieved between the operator and the technical system. The results section continues with examples of how automatic functions are visualized in each domain and how these interfaces can be connected to the domain characteristics and tasks that they are to support.

Each of the result sections are divided into physical-, control system-, operator- and task characteristics in accordance with the human-machine system model introduced in figure 1.

4.1 Results from the domain comparison

In table 1-3, the grading (high, average, low) for each factor from physical system, control system and organization/operator respectively are assembled. These ratings have been used as a basis for the results presented in section 4.2-4.3.

Table 3. Domain comparison of physical process properties. H =high level, A =average level, L =low level

PHYSICAL PROCESS PROPERTIES	Complexity															Dynamics					
	3a. Number of objects to monitor and control			3b. Coupling between objects			3c. Predictability in connections between objects			3d. Dependency between objects			3e. Influence from variations of external factors			3f. Stability (ability to maintain structure)			3g. Rate of change of process variables		
	H	**A**	**L**	**H**	**A**	**L**	**H**	**A**	**L**	**H**	**A**	**L**	**H**	**A**	**L**	**H**	**A**	**L**	**H**	**A**	**L**
Nuclear power	H			H				A			A			A		H				A	
Refinery	H			H				A			A			A			A		H		
Heat & power	H				A			A		H			H			H				A	
Aviation – Cockpit			L		A		H				A		H				A		H		
Shipping – engine CR			L		A		H					L	H				A			A	

Table 4. Domain comparison of control system properties. H =high level, A =average level, L =low level

CONTROL SYSTEM PROPERTIES	Automation												Proximity			Measurement									Interaction		
	4a. Collection of data			4b. Analysis of data			4c. Decision making and selection of action			4d. Performance of actions			4e. Proximity to physical process			4f. Precision of measurement			4g. Time from control action to finished action			4h. Accuracy of the control system's action on the physical process			4i. Amount of time the operator interacts with the control system		
	H	**A**	**L**	**H**	**A**	**L**	**H**	**A**	**L**	**H**	**A**	**L**	**H**	**A**	**L**	**H**	**A**	**L**	**H**	**A**	**L**	**H**	**A**	**L**	**H**	**A**	**L**
Nuclear power	H				A				L		A				L		A			A			A				L
Refinery	H				A			A			A				L		A		H				A			A	
Heat & power	H				A				L		A			A				L		A			A			A	
Aviation – Cockpit	H				A			A			A			A			A		H			H					L
Shipping – engine CR		A				L			L		A				L			L		A			A			A	

Table 5. Domain comparison of operator and organisational properties. H =high level, A =average level, L =low level

OPERATOR and ORGANISATIONAL PROPERTIES	Operator properties						Organisational properties								
	5a. Level of generic education			5b. Level of specialised education			6a. Percentage of working time the operator performs monitoring tasks			6b. Level of team work required to perform tasks			6c. Level of operator work rotation		
	H	**A**	**L**	**H**	**A**	**L**	**H**	**A**	**L**	**H**	**A**	**L**	**H**	**A**	**L**
Nuclear power		A		H				A			A				L
Refinery		A			A		H				A				L
Heat & power		A		H				A			A		H		
Aviation – Cockpit	H			H				A			A				L
Shipping – engine CR		A		H					L		A		H		

4.2 Results - levels of automation and function allocation

This section describes the levels of automation that are used in each of the visited control room environments. Each domain is described using the human-machine system model in figure 1 as a basis. According to Parasuraman et.al (2000) four basic types of functions that can be automated; information acquisition, information analysis, decision making and action selection and action implementation. Each of these functions have their equivalents in the action-perception cycle (Neisser, 1976).

The allocation of tasks and functions is closely connected to levels of automation since the allocation is the actual choice of what LoA to use. This section focuses on what principles that are used when allocating tasks and functions to either the operator or the automatic system. The efforts made to find a balance between human and machine elements to minimize automation problems is also discussed.

4.2.1 Refinery

Physical characteristics and level of automation

According to the domain comparison, a refinery contains a relatively high number of objects to monitor and control. There is a high coupling between the objects and the rate of change in process variables can be high. The predictability, dependency between objects and the influence from external factors is estimated as average. This means that the level of complexity of the refinery process is in parity with the process in a nuclear power plant.

Control system characteristics and level of automation

In a refinery, the collection of data is more or less completely automatic using sensors. Alarm systems analyse the data and support the operator in the decision making process in case of a failure. Procedures are also used as support. Actions are performed remotely from the control room but field operators are also present in the plant. The remote control of the refinery process is to some extent a result of the high use of automation, with safety as a driving factor. The large time delay from a control action until feedback is received can make the monitoring difficult since a long time perspective is necessary to notice changes that takes place over time.

The introduction of dynamic matrix control (DMC) in the studied refinery implies that the operators are further relieved from control actions, which can affect the ability to maintain necessary skills.

Operator and organisational characteristics and level of automation

When using highly automatized systems, the operators' level of education has to be in line with the technology that is introduced to enable understanding and effective problem solving. According to the operators, when introducing the DMC in the studied refinery control room, the control room operators are to report problems with the DMC to engineers that will adress the problem. There is an apparent risk with this way of organising work while it can deprive the operator role by removing stimulating tasks. A preferable solution would be to educate the operators to enable them to jump-start problem solving tasks until further assistance can be attained.

Task characteristics and level of automation

Two typical tasks were identified in the domain comparison; monitoring/optimization and handling of disturbances. In the refinery company in the study (Preemraff, Lysekil), a modern automation system for advanced control (dynamic matrix control or “DMC”) had recently

been implemented to perform the optimisation task. The DMC optimize a section of the refinery continuously. Operators should interfere with the DMC as little as possible since the optimization process is done more efficiently by the automatic system. In case of a failure the operators should revert to a lower level of automation and wait until assistance with correction of malfunctions in the advanced control system is received from the process department. Operators state that the loss of skills over time is a concern since the work is performed as passive monitoring with small possibilities to practice manual actions. The ability to monitor the DMC's automatic actions are however perceived as good since it is possible to see when the DMC make changes on process variables, for example when an increase or decrease in material feed occur.
From the process department's point of view, the risk of automation problems is handled as a question of operator training. The product quality enhancement when using the DMC compared to manual operations is substantial and the economic benefits of the DMC overshadow the loss of operator skills. To compensate the eventual loss of skills and knowledge, simulator training will be used to withhold operator competencies and make up for the lack of experience gained from manual operations.

Allocation of functions
Despite of the high complexity of the refinery domain, there is a trend to allocate many functions to the control system – leaving the operators to monitoring tasks. The advanced functionality of the control system offers the refinery process to be controlled without interference from human operators for long periods. The reason for allocating control to the control system is its' superior ability to optimize the refinery process compared with human manually controlled optimization.

In the studied refinery control room eventual problems with operators loosing their skills due to the advanced control system with high level of automation were considered as an educational or training issue. According to managers, if the operators were given more education, they should be able to handle failures in the automatic control system and simulator training, skills should be maintained. There is a strong technological focus which driving the allocation of tasks and functions. The high level of automation ensures high quality products through fine tuning of process parameters. The automation is regarded as superior compared to a human in performing these control tasks. The operators' role is to monitor the process for deviances and act on alarms from the control system. The process is divided into process areas where there are two operators in each area. The whole control room hosted approximately 10 operators.
This indicates the use of a "left-over" allocation principle where everything that can be automated is automated and the tasks that couldn't be automated is left to the operator. No signs of typical automation problems could however be found

The control room team were about to receive simulator training to compensate for the lack of occasions when manual tasks have to be performed.

4.2.2 Heat & power

Physical characteristics and level of automation
The domain comparison show that the number of objects to monitor and control in a thermal power plant is in parity with a nuclear power plant. The coupling between objects and predictability of connections is estimated as average. The dependency between objects and the influence from external variations is estimated as high. The main contributor to the complexity of a thermal heating power plant is the number of objects to control – which is

higher when a high level of automation is applied. The significant influence from the variations of external factors such as weather makes operations very dynamic. The plant operators continuously have to account for changes in heat and power demand that changes with the weather and season.

Control system characteristics and level of automation

The control system characteristics found in the domain comparison show a high similarity to the nuclear power domain. The physical process is normally closer to the operator compared to a nuclear power plant. There are also thermal power plants that are remotely controlled on distances of several kilometres that require extensive use of automation (i.e. Rya Kraftvärmeverk in Göteborg). Where plants are built to be controlled completely on remote, often still a few operators are positioned at the plant since the remote control is considered too risky. The avoidance of using the remote control indicates the importance of adequate trust in an automatic system. If the automation is not considered as reliable, it will not be used. Over reliance on automation is equally problematic since it can create skewed expectations on the automation's functionality and how it has to be monitored. The precision of measurements does not have to be as high as in the nuclear domain, but there are applications (e.g. environmental emission measurements) where high precision is required.

The amount of time the operator has to spend interacting with the control system is generally higher than in a nuclear power plant due to the nuclear power plants running stable over longer periods of time, while the load in e.g. thermal heating plants fluctuates with weather and power demand during different periods of the day. Heat and power plants also frequently change the fuel type used due to changing market prices. The quality of the fuel used can also vary, which requires additional monitoring of the combustion process.

Operator and organisational characteristics and level of automation

The only item in that differs from the nuclear domain in operator and organisational properties are the level of operator work rotation. The operators often split their time between performing monitoring tasks in the control room and working as field operators in the plant. This maintains the operators' mental model of the plant's physical arrangement and creates a job with variety.

Task characteristics and level of automation

In the heat & power domain automation sequences are used in a number of tasks. These are often connected to specific equipment and are not controlling larger parts of the process.

Examples where automation are used is sequences for start/stop of boilers and soot blowing to clean the boilers from carbon deposits.

There seem to be little concern about possible negative effects of automation, probably due to the relatively low criticality and safety implications in case of a failure compared to high risk domains such as a nuclear power plant. Also, automatic sequences are used within well defined parts of the process. This makes the sequence workflow easy to check and follow that the desired state has been reached. When using automatic sequences, the automatic system collects information to decide whether conditions are fulfilled or not. The operator acts to correct errors and then restarts the sequence if conditions are not fulfilled. This means that the operator performs the analysis and decision making parts, while the automatic system performs the sequence actions.

Allocation of functions
In the heat and power domain, technology drives the allocation of tasks and functions. No specific consideration seems to be taken regarding how work is divided between humans and automation. The use of automation sequences adds a significant amount of utility and makes tasks performance efficient compared to manual operations.

4.2.3 Aviation

Physical characteristics and level of automation
Aviation represents a domain that is very different from a nuclear power plant. However, there are similarities as well. The pilots' work contains long periods of supervisory control. Periods of high stress can occur during critical situations due to the possibilities of severe consequences of a malfunction. The pilots frequently use procedures as support both in their daily work as well as in critical situations, and both pilots and nuclear power plant operators use simulator training as a means for education and practice. The pilots have to deal with conditions that can change rapidly due to external factors but the physical process as such is very different from nuclear operations.

Control system characteristics and level of automation
Together with the ship engine control room, the aviation cockpit is the domain with the least similarity regarding the control system according to the domain comparison. The aviation cockpit however has very well defined levels of automation, and the pilots' roles and how they are supposed to act when using a specific level of automation is defined in procedures and practiced during training. The pilots can choose from four different LoA; "basic manual", "guided manual", "directed automatic" and "managed automatic". Depending on the LoA the two pilots in the cockpit has to change their roles according to table 5.

Table 6. Pilot roles during different levels of automation

LoA	AP	FD and HUD	Pilot Flying (PF)	Pilot Monitoring (PM)
Basic Manual	Off	Off or not followed	Handles the flight controls	Monitors flight progress. Call out impending flight envelope deviations.
Guided Manual	Off	On	Handles the flight controls	Monitors flight progress. Sets up AFS on PF order.
Directed Automatic	On	On	Makes MCP/FGP selections. Monitors flight progress.	Monitors flight progress.
Managed Automatic	On	On	Makes input to FMS. Monitors flight progress.	Monitors flight progress.

AP: Autopilot, FD: Flight Director, HUD: Head Up Display, AFS: Automatic Flight System MCP/FGP: Mode Control Panel/ Flight Guidance Panel

Basic Manual means that the aircraft is manually operated with the steering column or joystick only using visual guidance without the flight director. This mode is mainly used when performing avoidance or escape manoeuvres.

In Guided Manual the aircraft is hand flown with the steering column or joystick but with assistance from the flight director. The guided manual mode is the normal mode when flying the aircraft manually in combination with auto-throttle. Since the pilots are encouraged to perform landings manually to avoid loss of skills, this mode is often used when landing.

In Directed Automatic the pilot uses the flight guidance panels to select heading, altitude etc and the autopilot performs the chosen actions. This level is used where short term objectives are being met. The directed automatic level is normally used in terminal areas and as a transitory level when flying below 10 000 feet and pilot workload does not allow for reprogramming of the flight management system.

In Managed Automatic the autopilot performs the actions that are programmed in the Flight Management System. The aircraft then follows a pre-programmed route. The managed automatic level is used to meet long term objectives. During climb, cruise and descent this level is used with the flight management system that has been programmed before the flight has started. The level can also be used during departure or approach if the flight management system has been programmed, for example during poor visibility.

Operator and organisational characteristics and level of automation

Professional pilots are highly trained through simulator training where critical situations are practiced. Pilots are also required to perform a number of flight hours to keep their pilot license. Communication between the aircraft and ground control stations are important to maintain safety. Pilot to pilot communication is also crucial to maintain situational awareness, for example regarding what mode or level of automation that is being used at the moment. Work rotation is not applicable during a flight since the specified roles are strictly connected to certain responsibilities.

Task characteristics and level of automation

A pilot's tasks can roughly be divided into pre-flight checking, take-off, cruise and landing. Four levels of automation are used in different situations. These are described in "*Control system characteristics and levels of automation*".

Allocation of functions

In the aviation domain roles and functions are explicitly described when using different LoA. For example, at the guided manual level the pilot monitoring (PM) will make the required automatic flight system changes and selection on the pilot flying (PF) orders. At the directed automatic level the PF will make the required automatic flight system entries and selections.
At the managed level, the PF will manage the flight path through manipulation of the flight management system and PF also performs the pre-flight programming. Entries in the flight management system on altitudes below 10 000 feet are performed by the PM on orders from the PF due to increased pilot work load on altitudes below cruise level. The PM monitors the flight path continuously and always has a display active showing the current flight path up to the next waypoint. The highest levels of automation are used typically during routine tasks with low variability of external conditions, i.e. visibility, weather etc. Pilots often tend to take back control from the automatic systems during critical situations. In some situations they could however benefit from leaving tasks to the automation, to get time to deal with the problem that has to be solved.

4.2.4 Shipping

Physical characteristics and level of automation

According to the domain comparison, the ship engine control room only has one similar property compared with a nuclear power plant. Apart from the nuclear reactor and the steam turbine, the technical equipment shows similarities for example in the electrical power supply system. The complexity is lower compared to a nuclear power plant, but the influence from external factors such as weather and wind is significantly higher.

Control system characteristics and level of automation

The ship engine control room controls the ship's main engine and its' auxiliary systems. The maritime application and its use of automatic systems are much alike the power and heat generating domain, although the technical system is contained within a ship. Many, but not all, functions on the ship are automated. For example, the operators still have to manoeuvre some valves manually, although they are represented in the digital control system. The mariners appreciate automation since it makes the job easier in many aspects. The ability to control valves and pumps remotely reduces the workload and the crew resources can be used more efficiently.

The improvements achieved with automation are greatly appreciated by the personnel, e.g. fewer equipment breakdowns due to better monitoring capabilities and early warnings. Disadvantages are also recognized such as deteriorated feedback when starting equipment from a remote location. This can be compared to manual operation where audible and perceptual cues can be captured and give direct indications on equipment status.

Operator and organisational characteristics and level of automation

A ship engine control room can be left unattended for long periods. In modern ships the engine crew can be alerted and view alarms in their cabins during night time. This reduces the necessary number of personnel.

Task characteristics and level of automation

The operators stress the importance of keeping an up to date mental model of the technical systems. The operators' ability to locate and recognize the physical equipment through recall and recognition when using the control room interface, is an important part of efficient problem solving. The mariners point out the importance of knowing your ship inside out to be prepared for unexpected situations. They recognize themselves in loosing knowledge over time, when not having to perform actions manually. A correct mental model, when you are able to visualize a piece of equipment and its position and function in the technical system, helps maintaining knowledge. According to the interviewees, reaching this state is however only possible through extensive experience and training.

Some examples of the out of the loop problem were found. Manual control has it advantages since it reduces the difficulty of reclaim control after a deviating situation. This problem seems to be tightly connected with loss of knowledge, while manual actions actively maintain knowledge.

Allocation of functions

In the maritime domain no specific strategy for allocation of tasks and functions has been found. In general there is a strong technical focus in the domain, where the latest technology sets the standards on new ships. The automation provider sets the standard for allocating functions to either the human or the automatic system. No specific measures are taken to achieve a balanced allocation between human and automation, rather the mariners have to adapt to the current technology.

4.2.5 Nuclear

The analysis of the nuclear domain has been delimited to the turbine side of the nuclear power plant. This limitation has been made since turbine operations are similar to other domains and therefore transfer of knowledge and experiences are feasible.

Physical characteristics and level of automation

The extensive number of objects to control in order to manage the nuclear power process demands for use of automation. A nuclear power plant is relatively stable and normally runs for long periods without transitions. The pace of changes can however be very rapid, which also demands for automation to give the operators time to make good decisions. The complexity of a nuclear power plant makes it difficult to predict all possible critical situations and how errors can propagate through the technical system.

Control system characteristics and level of automation

The automatic turbine system was chosen as an example of an automated system that uses sequences for start up and shut down of the turbine. The control of the automatic turbine system 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. In manual mode the operator uses the control room panels to control equipment, while in step-mode the semi-automatic step function is used and in fully automatic mode the operator can let the automatic turbine system perform longer sequences of actions.

Operator and organisational characteristics and level of automation

The nuclear power plant operators are highly trained and educated, mainly from internal education and simulator training. It is common to start as a field operator or mechanic and become a control room operator after several years of field experience. The work rotation is limited, but shift supervisors and some operators has the competence to assist 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 relieves the operators from constant monitoring activities.

Task characteristics and level of automation

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 increases, 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.

Allocation of functions

Within the nuclear domain there is a strong awareness of the importance of task and function allocation. This is due to the rigorous regulatory demands. The use of the NUREG guidelines directs what should be taken into account when tasks are allocated. A drawback with the guidelines is however that they are old and not up to date with the latest technology. The lack of hands on training of critical situations from real events is compensated by simulator training.

4.2.6 Analysis – Levels of automation and implications on control

The refinery control room visited in this case study used a very high level of automation during normal operations. The reason for the high level of automation is economical and quality benefits provided by efficient automation. However, the operators expressed worries for losing their skills of optimizing the production manually. The automation had been recently implemented and it was too soon to assess whether their concerns were justified or if the simulator training compensated adequately for the lack of manual real time practice. Anyhow, the operators concerns should be taken seriously since they can lead to the automation not being used to its full capacity – hence losing its' benefits.

In the heat & power domain in general, automation is used on separate and well-defined tasks performed in sequences. This seem to reduce automation related problems since it is easier for the operator to over look the whole chain of events of an individual task. Where sequences are not used, for example in advanced control automation used in the refinery the automation acts continuously to maintain the plant in an optimal state. It is important that the operators can monitor the continuous actions and not only the final output result advanced control automation to maintain their understanding of the process.

The aviation domain has a well-defined set of levels of automation that also makes the definition of the pilots' roles easier. In turn, well-defined roles facilitate the allocation of what tasks to be performed by the pilots and the automation respectively. Since different technical equipment is used for each level of automation, the shift between levels becomes apparent. To maintain their manual skills and compensate the negative aspect of the autopilot, pilots land the aircraft manually as often as possible. Practicing this type of manual take over is important to minimize the effects of out of the loop problems. By quickly reverting to manual control, the time to return to normal operating conditions can be minimised.

In the shipping domain, few automation related problems were found. This is probably due to the control room being situated in close proximity to the physical process. The operators can sense deviations through sounds and vibrations that divert from the ships normal behaviour. Thereby they receive high quality feedback from the controlled process. In the interviews, the crew stressed the importance of knowing the ship inside out. That knowledge helps identifying problems from early warnings and thereby mitigating unwanted consequences.

The domains that have been studied in the domain comparison show examples of similar automation related problems as has been found in nuclear power plant control rooms in earlier research. The problems that arise when automation is introduced, for example out of the loop problems and loss of skills, seem to be generic irrespective of domain. Therefore, the idea to study other domains to learn strategies and find examples of solutions can be considered as useful. The way functions are allocated between humans and machines in the studied companies are linked with the criticality of the controlled processes. High risk domains such as aviation and nuclear power are more aware of the pros and cons of automation due to the rigorous regulatory body. The power & heat and maritime domain do not have the same concerns, but acknowledges the increasing use of automation and need for possible considerations in the future. The allocation of functions in the studied domains is to a great extent technology driven. However, the nuclear and aviation domain are unique in their use of simulators and amount of training. Refinery also plan for using simulator training as new highly automated systems are implemented. The aviation domain is the only domain who actively encourage their operators to revert to manual operation (manual landing) to avoid loss of skill. The level of automation also directs how tasks and responsibilities are divided between the cooperating pilots.

4.3 Results - visualisation of automatic functions

This section describes how automatic functions are displayed in the studied domains. The differences and similarities in the automation interface that have been found are described and compared. Since only one control room environment from each domain was studied, the results cannot be generalised as typical for each domain. Large differences can be found within each domain depending on the design used by the control system supplier.

4.3.1 Refinery

The domain comparison indicates many similarities with a nuclear power plant. The process contains a significant number of objects that has to be monitored and controlled and there is a high coupling between different parts in the physical process. The numerous objects that has to be monitored combined with the limitations of visual displays units creates a risk of keyhole effects, where only a limited area of the process can be monitored at a time. In overview displays the whole process can be fitted into a single display unit but at the cost of process detail. The studied interfaces in the refinery domain consisted mainly of classical process based interfaces (figure 3). These displayed the physical layout and the object to object connections in the plant effectively. The process based interfaces does however not support the operator in knowing what is normal and whether a performed action has brought the process closer to the intended goal. This information has to be inherent in the operator's own skills and knowledge.

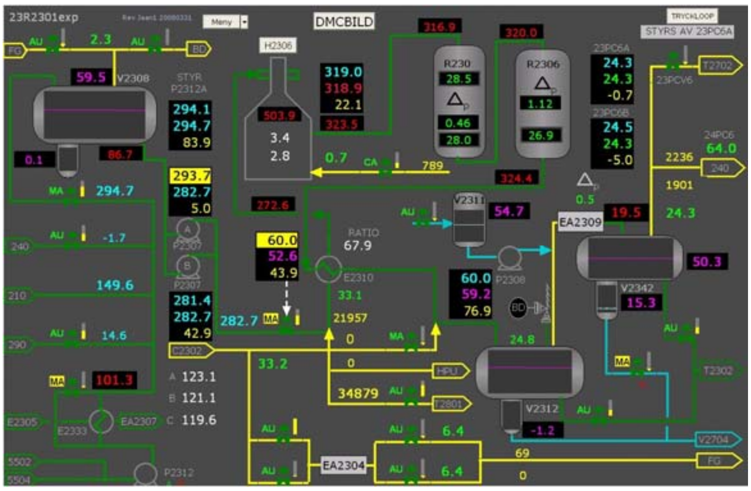

Figure 3. Example of a process based interface used in a refinery control room

The control system interface is arranged in three levels; overview-, work- and detailed screen. Apart from that, there are additional screens with information that the operator can access detailed information such as trends and additional text guidance. To reach awareness of the plants over all status requires a lot of navigation between different screens with today's interface, which is a disadvantage. Recent modernisations with better overview screens and personal configured screens are an attempt to improve this disadvantage.

With the introduction of advanced control features using DMC, the operator will be distanced from the tasks of analysing data, making decisions and selecting actions. The operators expressed concerns towards introducing a higher level of automation. According to the operators the DMC interface did not readily show how the automatic system was working and it was difficult to perceive the system's actions in the physical process. A deficiency with the DMC interface is that it does not reinforce learning. If the operators are to take over the DMC's functions when it is malfunctioning, the operators should also be enabled to learn how the system works. This could be improved by making the functionality visible in the graphical user interface.

4.3.2 Heat & power

A main difference between heat & power plants and nuclear power plants is the process criticality. The number of objects to monitor and control in a large heat & power plant is in parity with a nuclear power plant and apart from the nuclear reactor, the process of generating electricity is quite similar. Another difference is the monitoring of district heating nets where such systems are used. District heating nets can be spread over large urban areas with varying topological conditions, requiring operators to understand also how the terrain affects e.g. the pressure and flow in the district heating system. To depict this various pressure diagrams are used which also indicates that automatic controlled pumps are working accordingly. Within the power plant there are also automatic sequences controlling e.g. start up, shut down and soot blowing sequences (figure 4).

In the heat & power domain the precision of measurements is lower than nuclear applications in some aspects. For example, measuring the quality of the fuel being used can be difficult when not using fossil fuels. In biomass fuel the quality can differ significantly between different batches depending on what type of wood being used, the moisture content etc. This makes the process of adjusting burning variables troublesome since the fuel quality fluctuates. The fluctuating fuel quality together with costly governmental penalties for exceeded emission quantities (NOx, SOx and CO gasses) makes this a critical area for improvement. Today's heat & power plants relies on basic trending functionality to avoid excess emissions.

Since different fuels can be used and several boilers together with other sources of energy can be controlled from the same control room location depending on what is the most economical choice for the time being, the heat & power process in general is more dynamic compared to a nuclear power plant that produces more or less the same amount of electricity regardless of weather and market factors. This creates a larger variety in the control systems used. A combination of older and newer control systems is also often present in larger heat & power plants that have more than a single boiler. When different control systems are used and updated at different times it is important with a common company guide for how to design visual displays, or else a large variety of designs is likely to emerge.

The heat and power domain has similar operator educational levels compared to the nuclear domain however the company specific training is more extensive in the nuclear industry. The shift teams are organised with shift supervisors, technicians and engineers in both domains. The heat and power domain has a higher amount of work rotation were control room operators split their time between control room monitoring and field operations. In the nuclear domain, such rotation was not found in any of the studied plants. However, all of the nuclear power plant operators had a long background as field technicians.

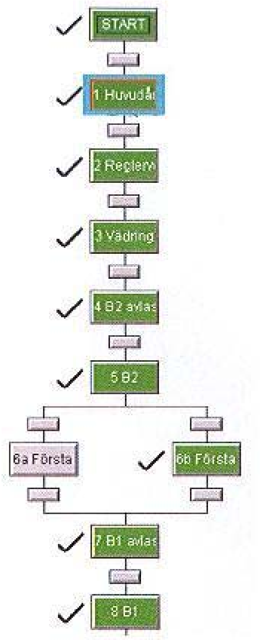

Figure 4. Example of automation sequence in a thermal heating plant

A typical task when automatic sequences are used is start-up or shut-down situations. Sequences are also used when the work procedure is very well defined. The automatic sequence interface is presented as a simple step by step sequence where it is possible to view the individual conditions to assess whether they are fulfilled or not (figure 4). The monitoring of continuous automatic controllers such as objects using PID control methods are usually left to the alarm system, meaning that the operator works reactively, since the alarm system calls the operator's attention when an alarm state already has been reached.

4.3.3 Aviation

A prominent difference between aviation and a nuclear power plant control room regarding the interface is the means for feedback. The pilots are located closer to the process (the aircraft) compared with the nuclear power plant operator. The difference is apparent when shifting the level of automation. For example, when shifting from managed automatic to basic manual mode, the pilot replaces the AFS with his/hers own navigation and vision abilities. However, many other tasks are cognitively similar. During cruising when using high levels of automation, the pilots are performing supervisory control as they monitor the aircraft status and the navigation performed by the flight management system.

Figure 5. The cockpit in a Boeing 737 simulator

The controls to manoeuvre the cockpit automation are spatially separated. In basic manual mode the PF uses the control column and the throttle together with additional manual equipment to control the aircraft. In guided manual, the PF is supported by the flight director and head-up display equipment. In directed automatic the auto pilot is engaged and the PF makes changes in the mode control panel, using buttons and knobs to adjust the altitude, speed etc. The PF then monitors the aircraft’s dials and meters for feedback that the auto pilot has reached the intended position. In managed automatic the PF makes input to the flight management system and then monitors that the automatic system follows the intended flight path. The spatial separation of all four levels of automation used has not been found in any of the other studied domains. Common tasks during each level of automation are described in section 4.2.3 “Aviation - Control system and level of automation”.

4.3.4 Shipping

Two ship engine control rooms were included in the study. A roll on-roll off (ro-ro) car and truck carrier ship and a ro-ro passenger ferry.

In the passenger ferry the most important parameters are available in analogue gauges in the control desk. These allow quick readings from a distance. The mariners are also experienced in hearing deviations in the sound from the engine, indicating malfunctions or non-optimal operation. These sounds can be felt in large parts of the vessel. The mariners in the ro-ro ferry were very pleased with the control desks in the engine control room. They argued that the physical layout gives a “superb overview” in comparison with computerized visual displays. The operator were placed in the middle faced towards the main switchboard and the engine controls. On the side walls the control desks hosted pumps, fans and bilge water valve indicators. The engine control room used a dark board configuration, allowing salient feedback from deviating indicators. The studied ro-ro ferry was built in 1983. Despite its age the ship had a control room layout that had been designed taking the operators’ needs into consideration.

Figure 6. Cargo ship engine control room

In the ro-ro car and truck carrier ship, the control room is sturdy built with the control system interface built into control desks (figure 6). The interface combines analogue hard wired gauges with a digital control system to maintain safety functions in case of loss of power.

The cargo ship engine control system's digital interface used a functional overview that was used to navigate further down in the display image hierarchy (figure 7). The cargo ship's control system interface was however perceived by the mariners as difficult to navigate since it had numerous inherent images to choose from, leading to a keyhole effect.

Figure 7. Cargo ship digital interface with touch screen.

The control system had displays dedicated to start and stop of automatic functions, for example all pumps within a subsystem was collected in the same display (figure 8).

Figure 8. Display showing the pump function

4.3.5 Nuclear

A set of typical tasks (start up/shut down of plant, handling of disturbances where safety functions are active, monitoring and optimization during full effect and periodic tasks) were studied in relation to the interfaces used to perform the tasks.

During start-up and shut-down the same indicators are used as during normal operations. This means that alarms and indications are not adapted to the transition states passed during a start-up or shut down. The operator has to remember a significant amount of information and check procedures continuously, since the support from the interface is adapted to full effect operation. Some assistance is however given by situation oriented interfaces that accounts for the transitional states. During a start-up/shut-down situation several operational transition states are passed which each have their own preconditions or rules. This is poorly indicated but it is not a problem according to the operators since this information is clearly communicated within the shift team. There is potential to improve the operator support during start-up/shut-down situations by improving the visualization of information presented in the control system interface.

Critical situations rarely occurs but are practiced during simulator training to achieve efficient handling if an accident or failure takes place. One of the most important features when the operators handle critical situations where safety functions have been activated is pattern recognition. This allows for rapid judgment of what further actions are necessary. According to the operators it is important that all safety functions are visible and spatially fixed to avoid that excessive time is spent on a safety function if there is a more important issue to deal with. For important situations there are situation oriented displays where all important information regarding that situation to allow all critical parameters to be monitored without spending time on navigating in the control system.

Another frequent task is the monitoring and optimization performed during full effect (normal) operation. During this task, the use of trend curves is the most important tool to follow parameters over long time periods. To allow for quick handling of occasional single alarms, the use of digital procedures directly linked to the alarm would facilitate and reduce the time spent on finding the correct procedure.

Periodic tests and object shifts are normally planned in advance and performed during calm operational periods, meaning that it is often simple to perform the action and wait for the expected process feedback. The object displays are important as support when performing the task. Since the tasks are recurrent it is easy to design displays since the procedure of actions and expected results are well known. It is however important that navigation is designed to allow for parallel viewing, for example during object shifts to avoid human error.

4.3.6 Analysis – visualisation of automatic functions

The refinery control room is the second most modern control room in the study. It had recently been modernised and large overview displays had recently been introduced. The refinery had also implemented a higher level of automation – the dynamic matrix control (DMC) or “advanced control”. The operators’ main automation related concern when using the DMC was to lose skill over time due to lack of manual practice and a reduced understanding of how the DMC optimised the process. Partly this is a training an educational issue, but to maintain the operators’ mental model of how the refinery process is controlled the graphical interface need to provide support regarding the functional structure of the system. An approach to address this problem is the use functional based displays. These can be designed using for example the Multilevel Flow Modelling method (MFM) (Lind, 1999).

In the heat & power domain the use of automatic sequences is a common feature. Since the automation sequences are well defined it is easy for the operator to overview. In modern control systems the descriptions of sequence stop criteria is also well described, facilitating the handling of malfunctions. Regarding display types, the process based displays are the most common display principle in the heat and power domain. They are created with the process flowcharts as a basis. Function oriented displays are also used, for example showing all pumps within a subsystem. Task based displays are rare but occurs as overview displays with key parameters or as sequences. Displays adapted for specific situations are mainly used for handling of disturbances.

Visualisation of automatic functions in the aviation domain mainly concerns the directed automatic and managed automatic automation levels where the flight director and head-up display are activated and the autopilot is engaged. In comparison with the process industry domain interfaces the flight director and head-up could be compared with a task based display type while the flight management system could be compared with a process oriented display type. The grouped buttons knobs in the cockpit resemble a functional oriented analogue interface. No situation oriented displays were identified. A positive aspect of the spatial separation of the automation equipment interfaces in the flight simulator is that it allow for the PM to see what level of automation is used by the PF, which would require active checking if the level of automation were chosen in a single digital display.

The roll on-roll off car carrier m/v Fidelio was built in 2007 and is the engine control room is thereby the most modern in the study. The digital control system interface was integrated in the control desk and only one monitor together with a smaller touch screen display was available to view the control system. The lack of additional monitors probably contributed to the keyhole effect since the operators often had to go back and forth between different displays. The digital control system could also have benefited from more extensive use of keyboard or graphical short cuts to facilitate the navigational task. The main finding from the engine control rooms is how the operators to a great extent relied on multi-modal feedback from the ship. Vibrations, sounds and visual feedback from the technical system were as least as important as the measured values displayed through the control system interface. The close proximity to the engine and auxiliary systems and the operators' regular turns through the ship might be a contributing factor to why no typical automation related problems were found in this domain.

5 Discussion

5.1 The domain comparison

To achieve a relevant domain comparison it was necessary to identify factors that are common for all of the studied domains and that reflect how the human-machine system works in relation to the use of automation. An advantage of the method for comparison is that it allows for a structured and systematic comparison of system influencing factors. Without the structured approach the comparison would be difficult to repeat for different domains. It also provides a quantitative measure of the included factors, although the scale (high, average, low) is coarse and the choice of level and the factor comparison is made in qualitative way. A fact that was realized after the comparison had been made was that the difference between work settings within the same domain could be larger than the difference between settings in different domains. This shows that it is the work setting characteristics that are assessed, and hopefully that stereotypical views of the whole domain thereby can be avoided. Drawing conclusions regarding a whole domain based on a few examples will not give validity, but to collect ideas and experience it is a viable method. The major drawback of the method is that it is time consuming and that it can be difficult to know how to rank each factor. It is necessary to start with the domain that will be used as a reference since the rankings are relative rather than absolute. To summarise, the method for domain comparison proved useful as a systematic tool for describing and comparing work settings, but improvements could be made to make the method more time effective.

5.2 Levels of automation & function allocation

The choice of what level of automation to utilise and where to allocate tasks or functions is mainly driven by economic interests rather than balancing by taking human cognitive abilities into consideration. If new automation technology will generate more profit by more efficient control it will be implemented irrespective of automation problems affecting the human part of the work system. The tendency shifts with increasing system criticality where human are in the system as the last line of defence against disaster (e.g. aviation and nuclear domains). In these domains the human contribution to system safety is considered earlier in the development process and can thereby influence the design of technology to a greater extent. The question of how to find the optimal level of automation is not trivial. Firstly, the concept of “optimal” has to be elaborated. The level of automation and function allocation can be chosen to maximise the short term economical benefit, but it can also be chosen to maximise for example safety. In this context it seems reasonable to maximise the over-all system performance, including safety and the operators working conditions. This also has the potential to give long term economical profit since lost production time caused by human mistakes can be minimised. Also, highly motivated personnel with interesting jobs tend to stay within the company, maintaining operating experience and skill which reduce costs for education and building up the experience of new operators.

5.3 Visualisation of automatic functions

The most common way of presenting information in control room environments is the process based interface. This way of depicting the controlled process is basically built on the construction blueprint and then transferred to the computer screen. This is an efficient way for the engineering designer to construct the user interface. However, this approach is often applied with too little concern regarding the operator as a user that has varying information needs depending on the task. For example, optimization of the process and obtaining status update are two tasks with varying information needs. Optimization requires detailed information on specific values and how a specific process parameter affects other parameters in the process. Status update on the other hand, requires an overall picture of key parameters that can be integrated from several other process values – there is no need for detailed information since the goal is to acquire status at a glance. Visualising automatic sequences can be considered well suited for a combination of task based and functional oriented interfaces since sequences have to be well defined and are repeated similarly each time they are performed and the automation functionality should be visible to support understanding and learning. When using sequences the temporal dependence is of special importance for the operator to maintain situational awareness. The operator has to be able to see what has happened, what is happening and what actions that the automatic system will perform in the near future. The possibility to see what criteria the automatic function acts upon is also important to understand the course of events in case of a failure.

In general, the combination of different types of interfaces (functional, ecological, situation, process- & task-based displays) is rarely motivated explicitly in the process industry domains. In the aviation domain, it is evident that there is a longer history of applied human factors engineering research that has affected how human needs are met in the cockpit. In the process industry domains there is a high dependence on what the control system/automation provider delivers, and it is often difficult and expensive to change the design after it has been implemented. This makes it difficult and expensive to change the design in retrospect. It is therefore often the operators that have to adapt to the technology than vice versa.

By combining the interface types mentioned above, different aspects of operator work can be supported. No single interface type can however support all operator needs. Different interface types are suitable for different tasks and situations. To improve the control system design work process and to facilitate the choice of when and why to choose what interface type for automation control systems, a description of how to support the operators' mental models is necessary. For example, the operator's model of the physical structure in a plant can be supported by a process based interface since it depicts connections between objects in the technical system. The operator's functional model can be supported by a functional oriented interface, where the operator can monitor and control how the system's purpose is fulfilled. The task based and situation oriented interface types supports the operator's memory of what is important and what procedural steps that needs to be performed to achieve a certain goal. In this respect, the ecological interface type can be viewed as an attempt to bridge the gap between physical, functional and task based interface types since the ecological approach builds upon the physical and functional constraints (by making use of the means-ends/part-whole decomposition) and at the same time address the problem solving task during unexpected events. To summarise, matching task goals and task characteristics with a suitable type of interface design is necessary to achieve a control system that supports the operators work. To have an impact, this demands a work process where the human factors perspective is considered early on in the development process since it necessary to take into account both how the technical system is designed and how the organisation wants the work to be performed.

6 Conclusions

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

The method for domain comparison proved useful as a systematic tool for describing and comparing work settings, but improvements could be made to make the method more time effective.

How do different industries try to achieve optimal level of automation?
No single domain studied in this project can be said to be in the lead regarding automation related issues from a human factors perspective. It is however possible to find ideas on how to support human supervisory control of automatic systems across domains. How to solve different issues are dependent on the goal chosen to be achieved (e.g. high safety standards, economic profit, a motivated work force, etc.). The challenge lies in finding a balance between these factors.

How do different industries allocate tasks and functions?
Among the studied settings, the left over principle was the most commonly used. The acknowledgement of the human contribution to more than as a last line of defence was higher among the high risk settings.

What differences and similarities regarding visualisation of automatic functions can be found across safety critical domains?
The display types (process based, functional oriented, situation oriented and task based) could be identified irrespective of domain. The detailed design naturally differs depending on the application.

How well do the visualisations of automatic functions support the tasks and situations that operators deal with?
If the display types (process based, functional oriented, situation oriented and task based) are applied so that they correspond to the same level of abstraction as the technical system, each display type seem to support the operators' mental models in an efficient way. No single display type can however readily match all levels of abstraction at the same time – all display types are still needed and serve different purposes.

References

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

Burns, C.M., & Hajdukiewicz, J.R. (2004). Ecological interface design. Boca Raton, Fla.: CRC Press.

Christoffersen, K., & Woods, D.D. (2002). 1. How to make automated systems team players, Advances in Human Performance and Cognitive Engineering Research (Vol. 2, pp. 1-12).

Endsley, M.R., Jones, D.G., & Bolte, B. (2003). Designing for situation awareness. London :: Taylor & Francis.

Frohm, J. (2008). Levels of Automation in Production Systems. Chalmers tekniska högskola.

Grote, G., Ryser, C., Wafler, T., Windischer, A., & Weik, S. (2000). KOMPASS: A method for complementary function allocation in automated work systems. International Journal of Human Computer Studies, 52(2), 267-287.

Hollnagel, E., & Woods, D.D. (2005). Joint cognitive systems: foundations of cognitive systems engineering. Boca Raton, FL:: CRC Press.

Lee, J.D., & See, K.A. (2004). Trust in automation: Designing for appropriate reliance. Human Factors, 46(1), 50-80.

Lind, M. (1999). Plant modelling for human supervisory control. Transactions of the Institute of Measurement and Control, 21(4), 171-180.

Neisser, U. (1976). Cognition and reality: principles and implications of cognitive psychology. San Francisco: Freeman.

Parasuraman, R., & Riley, V. (1997). Humans and automation: Use, misuse, disuse, abuse. Human Factors, 39(2), 230-253.

Parasuraman, R., Sheridan, T., & Wickens, C. (2000). A model for types and levels of human interaction with automation. Systems, Man and Cybernetics, Part A, IEEE Transactions on, 30(3), 286-297.

Rasmussen, J., Mark Pejtersen, A., & Goodstein, L.P. (1994). Cognitive systems engineering. New York: Wiley.

Sheridan, T.B. (2000). Function allocation: Algorithm, alchemy or apostasy? International Journal of Human Computer Studies, 52(2), 203-216.

Wickens, C.D., & Hollands, J.G. (1999). Engineering psychology and human performance. Upper Saddle River, NJ:: Prentice Hall.

Title	Automation strategies in five domains – A comparison of levels of automation, function allocation and visualisation of automatic functions
Author(s)	Jonas Andersson
Affiliation(s)	Division Design & Human factors Department of Product and Production Development Chalmers University of Technology SE-412 96 GÖTEBORG, Sweden E-mail: jonas.andersson@chalmers.se
ISBN	978-87-7893-309-6
Date	January 2011
Project	NKS-R / AutoStrat
No. of pages	37
No. of tables	6
No. of illustrations	7
No. of references	15

Abstract

This study was conducted as a field study were control room operators and engineers from the refinery, heat & power, aviation, shipping and nuclear domain were interviewed regarding use of automation and the visualisation of automatic functions. The purpose of the study was to collect experiences and best practices from the five studied domains on levels of automation, function allocation and visualisation of automatic functions. In total, nine different control room settings were visited. The studied settings were compared using a systemic approach based on a human-machine systems model.

The results show that the "left over principle" is still the most common applied approach for function allocation but in high risk settings the decision whether to automate or not is more carefully considered. Regarding the visualisation of automatic functions, it was found that as long as each display type (process based, functional oriented, situation oriented and task based) are applied so that they correspond to the same level of abstraction as the technical system the operator's mental model will be supported. No single display type can however readily match all levels of abstraction at the same time – all display types are still needed and serve different purposes.

Key words: control room, automation, function allocation, visualisation

Available on request from the NKS Secretariat, P.O.Box 49, DK-4000 Roskilde, Denmark.
Phone (+45) 4677 4045, fax (+45) 4677 4046, e-mail nks@nks.org, www.nks.org