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User interface solutions for supporting operators' automation awareness in nuclear power plant control rooms

Department of Automation and Systems Technology

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ABSTRACT OF THE
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This thesis discusses the effects of nuclear power plant control room digitalization and of increasing control room automation on the operator work. The concept of automation awareness is introduced and automation awareness is defined as a part of situation awareness. The development and maintenance of automation awareness is considered to be a continuous process that comprises of perceiving the current status of automation, comprehending the status and its meaning to the system behaviour as well as estimating the future statuses and their meanings. The human operator is seen as a part of the system, and their decisions and actions affect the system state.
The questions of what is sufficient automation awareness and how to examine the acquired level of automation awareness are addressed briefly. Sufficient automation awareness is defined as the operator's understanding of automation, their skills to interact with it and their will to cooperate with it on such a level that leads to safe and efficient operation of the nuclear power plant in all situations. Factors affecting the development and maintenance of the operators' automation awareness in a nuclear power plant control room are listed.
The thesis presents literature-based guidelines for successful human-automation cooperation as well as for presenting automation in control room user interfaces. The key contributors to a successful automation user interface are observability of automation, workload and failure management. In the practical part of the thesis, these factors were taken into account when designing and developing a user interface for a emergency diesel power generation system simulator. In developing the final user interface, user evaluation was utilized in addition to the literature-based theory. The ready-made user interface is presented and the design solutions are gone through especially in terms of the three mentioned guidelines.

Keywords: automation awareness, nuclear power plant, control room, human-automation cooperation, human-system interfaces

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Avainsanat: automaatiotietoisuus, ydinvoimalaitos, valvomo, ihmisen ja automaation yhteistyö, ihminen-järjestelmä käyttöliittymät

Foreword

This master's thesis was done in the Systems usability and activity-centred design team at VTT Technical Research Centre of Finland and the work is a part of HACAS (Human-Automation Collaboration in incident and Accident Situations) project related to The Finnish Research Programme on Nuclear Power Plant Safety 2011 - 2014 (SAFIR2014). The thesis was done in cooperation with Fortum, and without their support and the background material they provided, this work wouldn't have been possible.

I would like to thank my instructor, Paula Savioja, for her good advice and readily given guidance in the making of this thesis. I give my thanks also to my supervisor, Kari Koskinen, and my colleagues in VTT for their support and enthusiasm for the subject. Special thanks go to my beloved husband, Joonas Laitio, for being always ready to help with any language and LaTeX related issues.

Otaniemi, January 9, 2013

Paula Laitio

Contents

1 Introduction

This thesis aims for developing a method for presenting automation information in a nuclear power plant control room user interface in a way that supports the development and maintenance of the control room operators' automation awareness. The user interface developed within this thesis will be used in research purposes only.

Currently the Finnish nuclear power plants are experiencing a major automation reformation. Digital automation is gaining foothold in the plants and safety automation will be developed to meet the requirements of defence in depth strategies[1]. Along with these changes the amount of automation in the plants is growing, the role of automation is changing and new control room user interfaces are introduced. This will affect the interactions between control room operators and automation as well as the automation competence required from the operators. As the significance of automation is increasing greatly, it is assumed that the operators will need to understand it more deeply than before. Besides being aware of the process the operators will need to be aware of the automation controlling it. This leads to redefining the concept of situation awareness by introducing *automation awareness* as its subconcept that needs to be taken into account when designing the automation and user interface solutions for modern control rooms.

Master's thesis is a part of HACAS (Human-Automation Collaboration in incident and Accident Situations) project that is related to The Finnish Research Programme on Nuclear Power Plant Safety 2011 - 2014 (SAFIR2014). The project tries to answer the changes happening in the plants by gathering knowledge of factors related to control room automation and its effect on operator work. Master's thesis is related to research on automation awareness and its development. This research aims for deepening the understanding of factors affecting the operators' automation awareness in digital control rooms by, for instance, developing evaluation methods for automation awareness and competence. As a part of this research, a simulator environment for empirically studying automation awareness will be designed and developed. The scope of the simulator has been selected in cooperation with Fortum and is the emergency diesel power generation system. The reference system for the development is the diesel system of Loviisa nuclear power plant. The master's thesis focuses on developing a user interface for the simulator.

As changes in nuclear power plant control rooms obviously have implications on safety as well as the efficiency of power generation and continuity of supply, thorough research is needed in order to manage possible challenges caused by digital instrumentation and control (I&C) systems and human-system interfaces (HSI). These kind of reformations haven't been made before, so there is little knowledge on risks associated with the changes and means of overcoming them. Also, the focus of control room design has traditionally been more on the technical issues than on human factors. The contribution of human operators is, however, essential to the safety and overall performance of nuclear power plants, so human factors research is

[1]Defence in depth concept aims for reducing the risks involved in nuclear energy production by building up several independent and redundant safety functions around the reactor core. For more information see [1].

required in order to reach a lasting solution. As some kind of guidelines for designing safe and efficient digital control rooms will be needed in the future, it is important to recognize the issues related to digitalization concerning operator work and develop methods for evaluating their significance on both safety and efficiency of nuclear power plants. As part of this research, this master's thesis aims for finding the factors affecting the operators' automation awareness in the context of control room HSIs, and for developing a user interface that supports the operators' automation awareness and its further development.

1.1 Purpose of the study and research questions

Purpose of this thesis is to design a user interface for the emergency diesel simulator environment and develop methods for presenting automation in the user interface in a way that supports the nuclear power plant control room operators' automation awareness. To accomplish this, a literature research on factors that affect the operators' automation awareness and the significance of automation awareness and competence on operator work as well as the design principles for human-automation interfaces is needed. Thus, the purpose of the study is both explorative and developing.

The research problem is to find a way of presenting automation information so that the operators gain sufficient level of automation awareness without facing the problem of information overload.

The following research questions arise from the research problem:

1. How can automation awareness be defined and what is sufficient automation awareness based on literature?
2. Which (user interface related) factors affect the operators' automation awareness?
3. How can user interface solutions support automation awareness and competence?

1.2 Structure of the thesis

The main parts of this thesis are the theoretical part consisting of sections 2, 3 and 4, and the practical part in Section 5. In addition to these, Section 1 introduces the reader to the topic by presenting background information and research questions, Section 6 goes through the results of the research by answering the research questions and Section 7 summarizes the whole research and discusses its credibility and validity, along with suggestions on future research.

In the theoretical part, issues related to changes in operator work, development of automation awareness and designing automation user interfaces are discussed. Section 2 presents the effects of control room digitalization and increased automation on operator work and discusses the potential issues related to them. In Section

3, the term automation awareness is defined. Subsection 3.1 discusses automation awareness as part of situation awareness, Subsection 3.2 raises the question of what is required for adequate automation awareness and Subsection 3.3 presents the factors contributing to the development of automation awareness. The cooperation between human operators and automation as well as guidelines for designing automation user interfaces are discussed in Section 4 and its subsections 4.1 and 4.2 respectively.

In the practical part, the simulator user interface is designed and developed. Subsection 5.1 presents the tools used for the development and Subsection 5.2 presents the reference system. In Subsection 5.3 the design process of the user interface is gone through step-by-step and both the initial display drafts and the final design are presented.

2 Effects of control room digitalization and increased automation on operator work

The "central nervous system" of a nuclear power plant is its instrumentation and control system that together with plant personnel senses basic parameters, monitors the plant's performance, integrates information and makes needed adjustments to plant operations as well as responds to failures and to off-normal events [2]. A traditional nuclear power plant control room with analog panels covering the walls can be seen in Figure 1. When control room I&C systems are digitalized, also the human-system interfaces in the control room are affected. The HSIs transfer from hard-wired to computer-based systems [3] so analog panels will be replaced with computer workstations. The operators will sit on their workstations and monitor the plant through screen-based displays selected from networks of multiple display pages, control will be done with soft controls through the computer workstations and paper-based emergency procedures are upgraded to digital procedures which allow the operators to view dynamic parameter values and take actions through links in the procedures [3]. Changeover from conventional to digital systems is not a straightforward process but needs lots of effort in both planning and implementing the changes. Partly due to the complexity of the transformation process, also hybrid control rooms that contain both digital and analog technologies do exist. The hybridity as such hasn't proved extremely problematic but some concern has been expressed over the possible confusion caused by exploiting different generations of technologies in a control room [4].

Figure 1: The control room of Loviisa nuclear power plant. Analog panels are covering the walls and the operating consoles. Picture is courtesy of VTT.

Due to tremendous flexibility offered by software-driven interfaces, a wide range of technological approaches can be used in the HSIs. There are options for both the display hardware and the formats with which to display data. [5] On the other hand, the strict safety regulations and standards related to digital HSIs may limit the options and even lead to cumbersome solutions here and there in the systems. The designers need to make compromises in order to both meet the safety requirements and create effective user interfaces. With emerging interactive graphic displays the traditional distinction between controlling and monitoring activities becomes blurred [5]. If the user interfaces for controlling and monitoring are too inextricable it may cause the operators to mix them up and make it difficult for them to understand which actions have an effect on the process and which do not. On the other hand, it can be questioned if the operator tasks actually need to be strictly divided into controlling and monitoring or can the future operator work perhaps be seen as a more uniform whole including simultaneous actions related to both tasks. Digital operating procedures already include dynamic information of the plant's state enabling the operators to gather data not only from the monitoring displays but also from the control displays. However, being limited by size, one display cannot contain too much information or it risks overloading the operators.

Digitalization of I&C systems and control room interfaces, as well as increase in automated functions aim for safer and more efficient power generation in nuclear power plants. As humans have traditionally been considered prone to errors, many fields have adopted automation long ago in order to remove humans from direct control and aid them with difficult tasks [6]. This approach is nowadays seen somewhat outdated as such but, nevertheless, positive consequences of automation additions and digitalization do exist; applying automation may indeed remove existing human errors and can reduce operator workload if well-designed [7]. In many cases automation additions to systems have also significantly improved system performance [6]. Digital instrumentation and control systems are considerably more powerful and functional than their analog predecessors. They enable precise monitoring and provide better data to control systems, thus supporting better performance. Digital systems also enable plant personnel to more effectively monitor the health of the plant and to anticipate, understand and respond to potential issues and problems in meeting both the production and safety goals. [2] Digital user interfaces can increase operators' situation awareness by increasing the amount of information the operators can acquire visually and, on the other hand, by minimizing the amount of information that needs attention in disturbance situations (e.g. through alarm filtering) [8]. Caution in filtering the information is, however, needed as imperfect cueing of high-priority information may cause important information to be missed and lead to decreased performance of the joint human-automation system [9]. The potential for misunderstanding can be minimized by using information presentation manners that are more consistent with the operator's mental model of the plant and processes than were the conventional manners [8]. As digital user interfaces are suitable for individualization they can even be adjusted to the demands of each working task and each user's preferences [10]. Improved integration of process measurements and information from various sources also support situation awareness [8].

Unfortunately, the effects of control room modernization aren't restricted to the above-mentioned positive consequences. Digitalization and new automation solutions affect the operator work in numerous ways related to the work environment, the organization and the individual. Bainbridge [11] recognized the ironies of automation already 30 years ago stating that even highly automated systems need humans e.g. for supervision, adjustment and maintenance thus making automated systems still man-machine systems. According to her, the more advanced a control system is, the more crucial may actually be the contribution of human operator. 30 years later, the ironies were addressed by Baxter et al. [12] and two fundamental present-day ironies were recognized: the opportunities for users to manually work with the technology are reduced and real-time monitoring of automatic actions is getting harder due to the efficiency of the technology. These issues result in decreased possibilities for the operators to intervene in case of an automation malfunction, thus discarding the human operators' ability to flexibly react to abnormalities and possibly prevent bigger accidents from happening [12]. Digitalization further emphasizes the role of human operator as with the increased use of computer-based interfaces cognitive and human information processing issues are becoming more significant as compared to considerations needed for conventional HSI design [5]. In the following, factors that are affected by the digitalization and/or increasing automation are presented. The factors are gathered from the literature and divided into three groups based on their target, which can be either the work environment, the organization or the individual operator. Changes in the factors can cause major issues in future if not properly considered during the design phase of new control room solutions.

Environmental and tool-related factors:

- Physical workspaces [3]

  Physical layout of the workplace [13]: Information is located in a computer system rather than in dedicated spatial locations spread out across control stations, which may cause loss of the ability to utilize well-learned rapid eye-scanning patterns and pattern recognition from spatially fixed parameter displays [5]. This loss of big picture and focusing on only small parts of the process at any one time is known as the keyhole effect [14].

- HSIs [3]

  Functionality of the HSIs [13]: screen-based displays and soft controls are used instead of hard-wired interfaces. Even though digital displays often try to mimic their analog counterparts to some point, new technologies still require the operators to learn a new way of operating the plant. Using a conventional panel, the operator could turn a knob while looking at changing parameters somewhere else whereas in a digital user interface the sense of touch cannot guide them. Digital world also offers a whole lot of completely new operating methods, the quality of which needs to be thoroughly investigated before introducing them to control rooms.

Method of information presentation [7]: digital user interfaces offer nearly infinite number of formats with which to display data (lists, tables, graphics etc.) [5]. This enables advanced displays but may also be overwhelming to the operator as they need to learn a whole new language of display formats. Information in digital user interfaces is typically presented in processed form which can obscure the meaning of the original raw data parameters [5].

- System properties

  System performance: as stated before, digital systems enable precise monitoring of the plant and better data for controlling [2] and automation additions have improved the system performance [6]. As human performance cannot be increased infinitely due to limited capacities of the human body and mind, this raises a question if the human operators can keep up with the digital systems. Instead of blindly aiming for the highest possible system performance one should optimize the overall performance of the joint human-automation system.

  Propensity for failures: when system complexity increases, the propensity for failures increases [6]. Degradation of the digital system may not be communicated to the operators, which can cause a delayed response and lead to more serious events [15].

Organizational factors and factors related to the ways of working:

- Personnel role [7, 16, 17]

  Functions and responsibilities of plant personnel: The role of people becomes more, not less, important as automation becomes more powerful [18]. Increased automation doesn't relieve the operators of tasks but shifts them from direct control to monitoring and supervision [5, 18, 19]. A common issue with advanced computer-based systems is poorly organized and ill-defined tasks [5, 20] as the operator may only be left with an arbitrary collection of tasks which the designer cannot think how to automate [11].

  Required qualifications [16]: the operator needs to understand and supervise a more fully integrated control room [7]. In complex modes of operation the human monitoring the system needs to know what the correct behaviour of the process should be, which requires special training or displays [11]. Even though information technology is nowadays part of our everyday lives, the increasing utilization of computers in the operator work requires the operators to adopt a new tool and learn how to use it efficiently. Former experience in working with computers can ease the adoption. It is possible that this favours the younger operators who not only might embrace new things faster but also have grown up in a computerized world.

- Operator tasks [3]

  Primary tasks [13]: the way of performing primary tasks (tasks directly involved with operating the plant such as process monitoring, situation assessment, response planning, response execution and control) changes due to digitalization [16].

  Secondary tasks [13]: secondary tasks (tasks related to interface management such as navigating through displays and searching for data, choosing between multiple ways of accomplishing the same task and deciding how to configure the interface) emerge in addition to primary tasks [16].

- Teamwork [13]

  Communication [3]: communication between operators may happen through the computer so delays in the communication subsystem may result in operator control action instability [15]. Due to keyhole effect the operators are no longer able to make interpretations of the tasks their co-workers are currently up to based on their physical location in the control room. Instead, verbal communication is needed.

  Cooperation with automation: automation has been widely incorporated to aid humans with difficult tasks. However, shortcomings in combined human-machine system performance have resulted due to problems in combining the automated system and human operator [6]. The operators may have difficulties understanding the automation [17]. When automation fails, the operators have to manually perform automation's tasks thereby changing the roles and responsibilities of crew members [15]. Introducing automation changes the type and extent of the feedback the operators receive, which may cause problems if manual control is suddenly needed [18].

- Procedures: computer-based procedures are used instead of paper [3]. This may affect the ergonomics of operator work as the operators need to read their instructions on computer screen instead of paper sheets. The display might also be smaller in size than is the paper so information is fitted on a smaller area. More memorizing will probably be required as the operators can't take the screen with them if they need to do something on the other side of the control room.

Cognitive and individual-related factors:

- Workload [7, 13, 16]

  Level of workload: well-designed automation can reduce operator workload but automation doesn't always result in a good level of mental workload [7]. Even in highly automated plants the operators still need to monitor the automatic system's activity and the higher the number of automated functions, the higher the number of activities to be monitored [21]. This may add the operator workload. Computer-based HSIs typically include much more information than conventional ones. Secondary tasks related to interface management increase the operator's cognitive workload if the information is not properly organized and presented [5]. In the experiment done in a hybrid control room by Savioja et al. [4], the task load of turbine operators using a digitalized user interface proved significantly higher than that of reactor operators who used a conventional user interface. Even the physical demand of the tasks was considered higher by the turbine operators even though they moved less than the other operators [4]. Too low workload due to passive monitoring, on the other hand, results in operator boredom which also is harmful for performance [3].

Type of workload: The shift from direct control to supervision and monitoring shifts the operator workload from high physical workload to high cognitive workload which impairs the operator's ability to monitor and process all relevant data [5].

Workload transitions: sudden loss of automation may cause a fast transition from low workload to high workload when the operators need to take on control [5, 17].

- Human errors: applying automation may remove existing human errors [7] but at the same time new types of errors emerge [7, 17]. Failures in automation system have proved to be difficult for the operators to discriminate from a process failure even though the new digital interface would have enabled the operators to detect that the failure in question was an automation failure [4]. This suggests that care should be placed on how to present the failures to the operators. Even a small system failure can lead to severe incidents as the operators may take inappropriate actions based on erroneous information from a malfunctioning system if they are not aware of the malfunction [15].

- Loss of skills [5, 17, 22]: Acting as a system monitor instead of a direct manual controller may cause erosion of skills to perform the needed tasks in case the automated system fails [5].

- Operator performance [7]: potential degradation or failure of digital systems could greatly affect the operators' performance [15]. Automated systems may fail to provide relevant information on possible failures thus degrading the operator performance as the operators can't detect the errors and intervene to carry out the correct manual task [8].

- Operator vigilance and complacency: During long-lasting automated working phases the human operators are unchallenged and become easily tired [10]. This leads into decreased vigilance and reduced ability to detect off-normal situations [5]. Even the simple situations may become too challenging to handle if the inattentive operators suddenly need to interfere due to a breakdown of the automated system [10]. Complacency can be seen as more consciously neglecting the tasks related to working with automation, such as gathering information and supervising the automated function [22]. This may happen for many reasons but, as vigilance, also complacency is associated with excessive use of automation. For example, when the operators don't feel themselves responsible for the function allocation between them and the automation, they become complacent and don't perform the required tasks [22].

- Situation awareness [5, 7, 16]: digital systems and increased automation may cause a disconnection from the plant and force the operators focus too much on the complex computer interface [3]. Poorly designed automation can take the operator out-of-the-loop which results in degraded situation awareness [17]. The operators playing a passive monitoring role may loose their awareness of the system and the dynamic features of the work environment [7]. Degradations of the sensor and monitoring subsystems as well as the automatic systems may lead to poor situation awareness as even a single failure can mislead the operators about the whole plant's state [15].

- Operator's feelings towards the system (e.g. trust [3, 22], satisfaction [7])

All the aforementioned factors contribute to the overall human-system performance, appropriate level of which is the key to successful, safe and efficient power generation in nuclear power plants. As automation is a key contributor to many of the factors, the potential issues related to them can largely be avoided with the operators' proper understanding of automation, skills to interact with it and will to cooperate with it. The combination of skills in, knowledge of and feelings towards automation can be referred to as *automation awareness*, a term that will be further explained in the following section.

3 Definition of automation awareness

Automation awareness is a term originally invented in the SAFIR programme to describe the operators' understanding of, trust in and cooperation with automation. The term emphasizes the fact that in the world of digital automation the operators' situation awareness is growingly related to the state of automation instead of focusing solely on the process parameters. Automation awareness is occasionally mentioned in other literature (e.g. [23]), too, but is not yet an established term as it hasn't been widely studied. It is, however, recognized that "in the world of increasing automation the phenomenon of system awareness exists in a wider (and growing) context of awareness of, through and perhaps even by automation" [24]. The following subsections will define automation awareness as is relevant for this thesis.

3.1 Automation awareness as a part of situation awareness

Situation awareness is a widely accepted, though debated, term for describing the understanding that a person has of the current situation they are in. According to Endsley (cited in [6]), situation awareness is formally defined as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future". It should be noted that this definition is originally derived from research in the military aviation domain and may thus not be suitable for process control as such [25]. In a nuclear power plant control room the operators need to know the plant's state in order to operate it [13]. The situation assessment in process control can be seen as creative problem solving including active exploration of the plant's state as a whole and problem representations of process operations instead of pure vigilance and computation of process parameters [25]. To construct a model of the plant's current situation the operators use their general knowledge about and understanding of the plant and how it operates. This general knowledge, also referred to as mental model, consists of the operators' internal representation of the physical and functional characteristics of the plant and its operation and can be built up through education, training and, most importantly, experience. [13]

Figure 3 uses Endsley's model (presented in Figure 2) as a starting point but brings it closer to process control domain. In Figure 3(a) the basic components of the situation assessment process are represented. The continuous nature of the development of situation awareness is emphasized. Instead of following a linear sequence of actions, the operators constantly update their mental model of the plant's state. Figure 3(b) represents situation awareness as a basis for decision making and execution of actions. Decisions can be made at any point of the situation assessment process as long as the operators have reached some level of awareness of the current situation. As a result of the operator's actions, the state of the environment changes and the received feedback again affects the situation assessment process. Figure 3(c) represents some tool-related, individual and organizational factors affecting the situation assessment and decision making process.

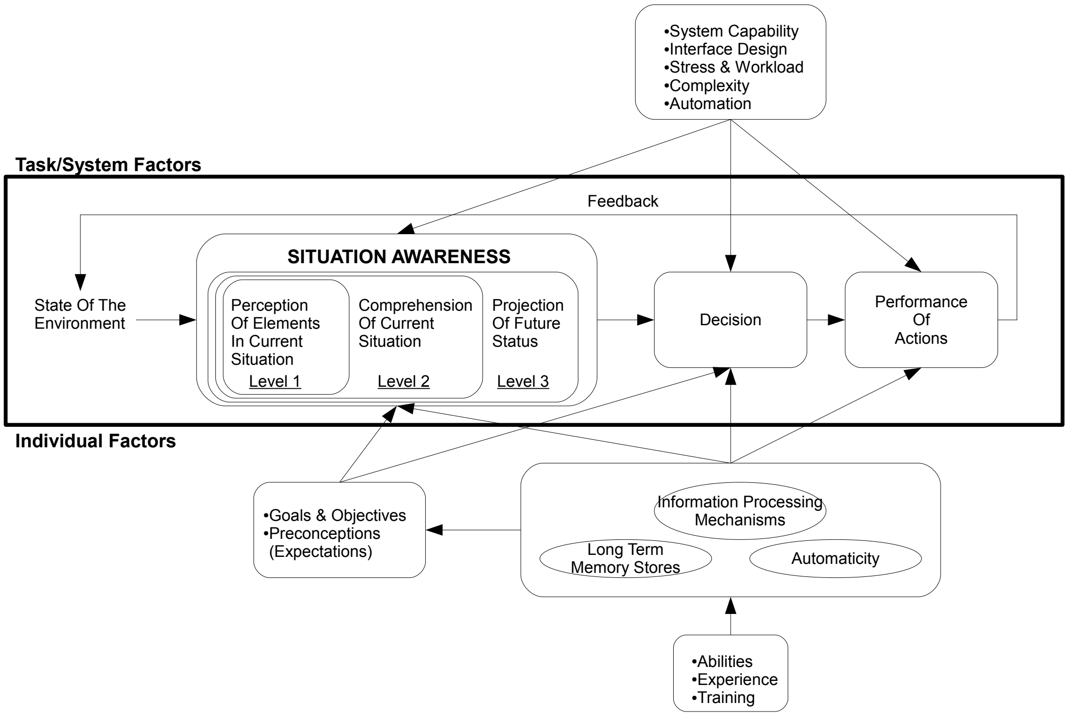
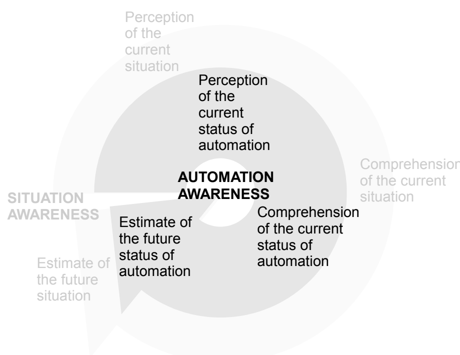


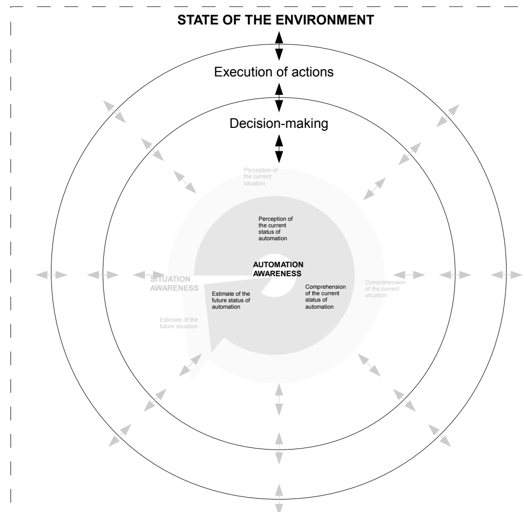
Figure 2: Model of situation awareness in dynamic decision making (from [6]).

Besides being necessary for appropriate decision-making and taking prompt measures at the situations [26], situation awareness is also an important indicator of the operator's overall performance [8]. A well-developed mental model combined with accurate situation awareness enable more open-loop performance, which leads to smoother and more anticipatory system control through the use of prediction and expectations to guide control responses [5].

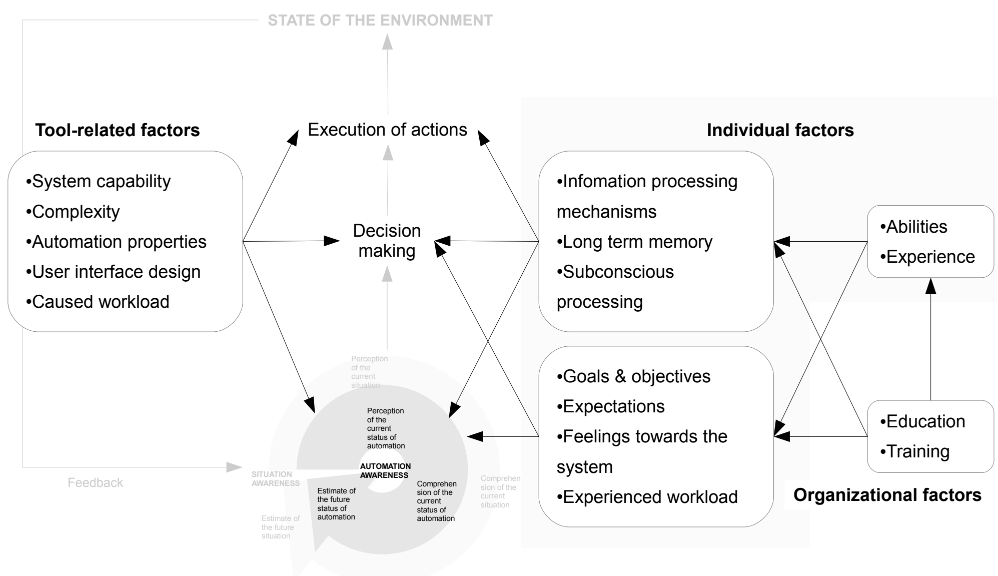
With automation taking more foothold in nuclear power plant control rooms, it is no longer enough for the operators to understand the process but they also need to know how the automation functions in order to develop a good mental model of the system as a whole. Even though not referred to as automation awareness, this need has been recognized widely. Already Bainbridge [11] noted that an operator will only be able to create successful new strategies for unusual situations if they have an adequate knowledge of the process. According to her, if system functions are automated, the operator may not be able to efficiently retrieve knowledge from long-term memory as the knowledge develops only through frequent use and feedback about its effectiveness. Also O'Hara and Hall [5] stress that the erosion of an up-to-date mental model is a central problem with poor allocation of function between man and machine. Later literature addresses problems related straight to inadequate understanding of automation. According to Skjerve et al. [21] a major problem with automation is that the operators can find it difficult to understand



(a) Automation awareness as part of situation awareness.



(b) Automation and situation awareness form a basis for decision-making.



(c) Factors affecting the development of automation and situation awareness.

Figure 3: The operators' automation awareness can be seen as a sub-process of situation awareness. Together the automation and situation awareness form a basis for decision making and execution of actions. The development of automation awareness as well as situation awareness is a continuous process to which many factors affect. Figure is based on [6].

what the automatic system is doing and thus to determine whether the system performs as required. Human errors due to misunderstanding automation have been reported in [2] and [19]. Questions like "What is it doing now?", "What will it do next?" and "Why did it do this?" indicate that the operator's understanding of automation is not sufficient as the operators ought to be able to understand what any automation scheme is doing behind the scenes [19]. Figure 3 also represents automation awareness as part of situation awareness pointing out that the operators also need to assess the automation's state in order to fully understand the situation.

The only way for the operator to track what an automatic system is doing, why and how it is doing it and what it will do next is a visualization of the systems in an interface [2]. This thesis aims for finding an effective way to visualize some automatic functions to the operators. The next section uses literature to define what the operators need to know about the automation in order to efficiently and safely operate the plant. In Section 4 guidelines for designing well-functioning human-system interfaces are presented.

3.2 What is sufficient automation awareness

It is widely agreed that understanding of how computer-based systems work and having a good mental model of automation activities is essential to proper monitoring, supervision and maintenance of plant systems as well as to correctly integrate information about the state of the plant and processes [8, 16]. Unfortunately, there are no precise guidelines or standards for what kind of information about automation really needs to be presented to the operators in order to improve their performance. The challenge is to provide adequate situation and automation awareness without overloading the operators so that their performance degrades instead of increasing [23]. Within digital systems it would be possible to offer very detailed information about the system's functions for the operators. It is, however, not necessary for the personnel to know the complex details of all the automation's operations but to understand the automation on such a level that they can effectively supervise it, understand the conditions where it may be unreliable and in what ways and be prepared for backing up the automation during potential failures [2]. In the fighter aircraft domain, where automation degradations are probably more common, it has been seen very important that the automated system is not perceived as a black box with no knowledge of how the system works. Helldin and Falkman [27] state that it should be easy for the pilots to create and maintain a mental model of the system, but also in this domain it is considered that the model itself can be simple and not contain information about every task the system performs.

Despite the lack of standards, some suggestions for obtaining sufficient automation awareness have been made. According to Whitlow et al. [23] "adequate situation and automation awareness is the union of current and near-term task information requirements as well as a general set of mission performance information" and can be obtained by meeting the following goals:

- maintaining an active and engaged human supervisor that is involved in the system workflow and aware of the environment as well as the automation's actions, intentions and rationale

- delegating some tasks to automation
- making the automation observable
- offering abstracted information that is distilled to the appropriate level of oversight

O'Hara and Higgins [2] have gathered an extensive list of information types that can be useful for the operators during autonomous operation. According to them the operators should know the automation's purpose, structure and interaction with plant systems and functions, not forgetting the current goal of the automation as well as its reliability in accomplishing the goal and the roles and responsibilities of all agents involved in meeting the goal. They also consider explanations of the automation's processes and their current progress as well as possible difficulties or failures as relevant information for the operators. For automation with modes O'Hara and Higgins suggest that the operator should know what the current mode is, how the automation's behaviour changes in each mode, how the automation's mode impacts the systems being monitored and/or controlled and how the operator's responsibilities change for each mode. Whitlow et al. [23] remind that the availability and quality of the feedback is, however, not the only thing that counts but it should also be taken into account how much cognitive effort is required to maintain awareness that leads to correct actions by the operators. They suggest that this kind of *actionable* automation awareness can be improved by providing appropriately abstracted status information, including meaningful confirmation that user input was understood, providing salient mode transitions and offering a preview of future automation activities.

One remaining question is how to determine if the operators' automation awareness really is on a sufficient level. According to Lin et al. [7] user satisfaction is a key measure of automation's success and needs to be taken into account as accurate as possible. It is, however, impossible for the users to estimate their satisfaction towards something they don't have appropriate knowledge or understanding of. Hourizi and Johnson [24] try to define the state of awareness more accurately by dividing it into four levels in which raw data from the environment has been 1) available, 2) perceived (perceptual awareness), 3) attended to in some manner (attentional awareness) and 4) subject to further, higher level cognitive processing (higher level cognitive awareness). Using this division, awareness breakdowns can be described in terms of the particular sub-process that failed:

- Level 2 failure: information was available but not seen
- Level 3 failure: information was picked up visually (or with other senses) but overlooked
- Level 4 failure: information was available, seen and attended to but its meaning or implication was not understood

Figure 4 represents the levels of awareness and possible awareness breakdowns. In order to reach the higher level cognitive awareness, the operators need to perceive the information, attend to it and process it further. Based on their definition, Hourizi and Johnson suggest that potential problems in maintaining awareness can be predicted with questions like “Is the user’s attention likely to be drawn to the relevant information source?” and “Is the information presented in such way that it can be easily processed by the receiver in terms of the implication for action it is intended to convey?”. This approach is also lacking quantitative measure of the operators’ automation awareness but, at this point, qualitative evaluation will be sufficient and perhaps even more valuable than quantitative. While the term is still developing, qualitative measures can also add to the definition of the term itself and not only be used as evaluation tools.

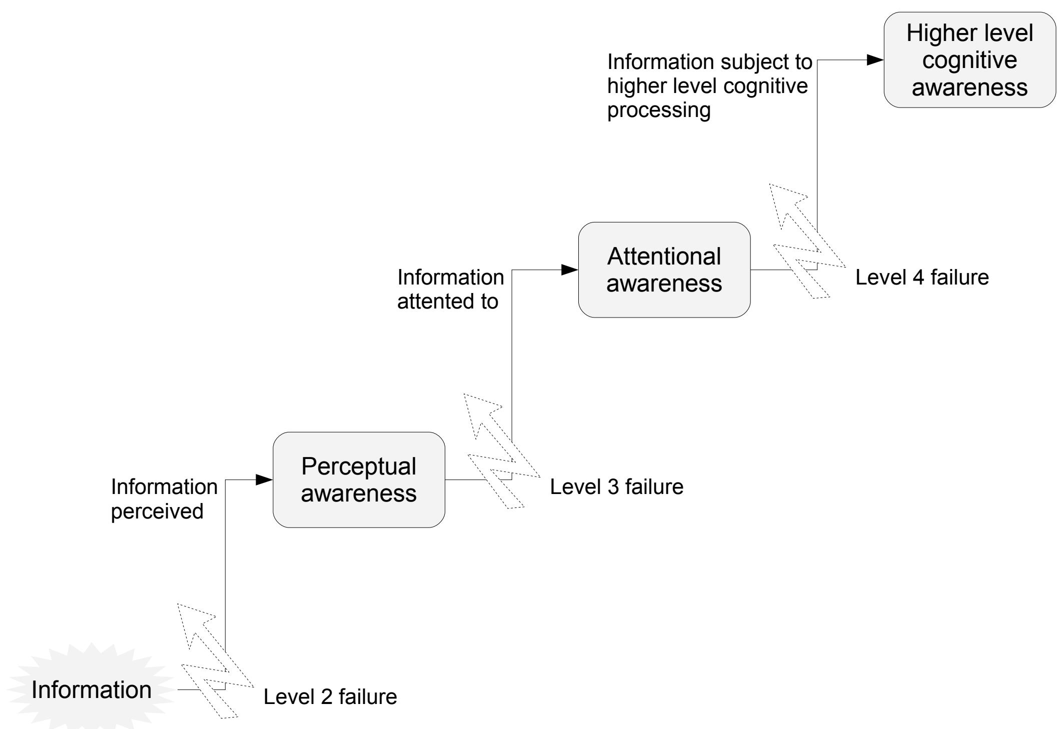


Figure 4: The levels of awareness and awareness breakdowns according to Hourizi & Johnson’s [24] definition.

3.3 Factors affecting the development of the operator's automation awareness

There are multiple factors contributing to the development of the operator's automation awareness in a nuclear power plant control room. Many of them are rather properties of the automation itself than characteristics of the presentation of automation in a user interface and should be taken into account already when designing the automated system. Operator training and other organizational factors are also key contributors in developing an adequate awareness of the automation. Shortcomings in the above-mentioned factors may partially be compensated with a well-designed user interface whereas a poor user interface can totally annul the advantages reached with proper automation design and training. Thus, user interface design is an important factor in the overall success of automation and proper focus needs to be put on it. Table 1 presents some factors that are known to have an effect on developing and maintaining the operator's automation awareness based on literature.

Table 1: Factors having an effect on automation awareness

Affecting factor	**Significance**
Level of automation [2]	The level of automation can vary from no automation to fully autonomous operation. Highly automated systems place the operators in strictly monitoring role, which leads to passive processing of information [6]. Automation tends to distance the operators from the details of an operation [2] as monitoring automation disconnects the operators' actions from the actions on the system and can thereby undermine their mental model [18]. At intermediate levels of automation the operators may be far more involved in the operation and their ability to interact with the automated system as well as to recover from and perform during automation failures is significantly improved [6]. In manual control perception directly supports control and control actions guide perception [18], which supports focusing on the task at hand.

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Affecting factor	**Significance**
Automation complexity [2]	Automation can be very complex as it may consist of many interrelated components and operate in many different modes [2]. Automation additions can also increase the complexity of the whole system [6]. As often only a partial or metaphorical explanation of the automated functions is provided for the operators, they may appear quite simple. Hiding the true complexity of the operation as well as the internal relationships and interdependencies between the automated functions from the operators may, however, make it difficult for them to really understand the automation. [2]
Modes of automation [2]	Multiple modes add to automation complexity. Automation can cause surprises by changing modes without the operators' commands to do so. Also, the operators may unintentionally select a wrong automation mode which may result in automation reacting differently than intended or expected. [2]
Functions of automation [2]	Automation can be applied to several cognitive functions (e.g. information acquisition or control). The selection of functions that are automated and the level of automation for those functions can have an effect on the operators automation awareness. [2]
Processes of automation [2]	Automation processes the information it gathers from the plant in order to accomplish a goal. These processes are the means by which automation performs its tasks and are thus an important aspect in understanding automation. [2]
Flexibility of automation [2]	Adaptive automation (automation with changing level) seems to have a positive effect on the operators' understanding of automation, situation awareness and ability to recover when automation fails. There can, however, be a cognitive cost to switching between levels of automation that can cause performance issues. [2]

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Affecting factor	**Significance**
Reliability of automation [2]	Reliability of an automated system impacts trust and the operators' use of it [2, 9]. Both complacency due to over-reliance in automation and lack of trust in automation may reduce the operators awareness of automation [6]. If the automation seems to be extremely reliable, over time the operators can become less concerned with and aware of the details of the operation. In making decisions under uncertainty, the operators may overvalue the data provided by automation and fail to seek out information independently. On the other hand, if the operators lack confidence in automation, they will not use it. Providing information about the automation's reliability under different situations can support appropriate trust calibration. [2] Conclusions can be drawn that proper calibration of trust may enhance the operators' automation awareness whereas proper awareness of automation can improve the trust calibration.
Other automation properties	Automation has been designed for predefined situations and can be expected to perform well under them but may behave unpredictably otherwise [2]. Automation may have inbuilt correction and compensation functions which can cause problems in the operators' awareness. Some systems may second-check the operators' actions and correct their possible errors thus preventing the operators from learning from their mistakes. This way the operators might repeat the errors without knowing it and loose their awareness of the correct actions. [28] Automation may also mask failures in other plant systems compensating for them. If the operators aren't aware of the compensation, this can be problematic when the situation reaches a point where the automation no longer can compensate it and the personnel need to take over. [2]

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Affecting factor	**Significance**
Feedback	Feedback from automatic activities is essential for maintaining awareness of the automation. Unapparent behaviour of automation devices may lower the operators' awareness of the goals of automation [2]. Automation additions may result in changes in feedback form or complete loss of feedback [6] as automation may lack communication of what it is doing and why, or communicates poorly or ambiguously [2]. Digitalization, on the other hand, offers new opportunities in providing feedback from automation. Appropriate feedback could help the operators in detecting automation degradations and, in case of complete failure, assessing the current status of the systems the automation was controlling [15]. There should also be an opportunity for the operators to communicate with the automation (e.g. by making queries) [2].
Workload	Automation awareness and workload are interrelated in many ways. The level of current workload can affect the development of the operators' automation and situation awareness be it high or low: with low workload the operators may have low awareness due to boredom, lack of attention and problems with vigilance whereas in high workload situations the operators may lack capacity to maintain awareness [8]. On the other hand, interacting with and configuration of automation may add to workload thus making maintaining the awareness even harder. Ironically, this interaction is often necessary in situations where the workload is already high. [2]

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Affecting factor	**Significance**
Training	Training is the base for understanding automation. Inadequate training (philosophy, objectives, methods, materials or equipment [2]) leads to inadequate understanding [6]. When the operators understand the purpose and the functioning of the automation, they can use it more effectively. Conditions for using the automation and conditions under which it shouldn't be used, as well as information about the algorithms and different modes of automation should be included in procedures and operator training. [2]
User interface	Poor interface design can significantly reduce the operators' situation awareness and awareness of the automation [6]. Problems can emerge if the HSI is not suitable for interacting with the automation but also if the automation's human-system interface is not properly integrated with the other HSIs in the control room. Poorly designed displays, display formats and display elements can cause important information to be missed or misinterpreted. The operators' ability to make safe decisions and actions may be limited due to not displaying important information available from the automation. [2]

As the focus of this thesis is on presenting the automation in an user interface, the other factors mentioned in Table 1 won't be further examined. The next section presents some guidelines and suggestions for designing an effective user interface for nuclear power plant automation. It is assumed that, by following those principles, a user interface that offers a decent view to automation can be developed.

4 Presenting automation in control room user interfaces

Digital I&C systems and human-system interfaces provide opportunities that could not have been reached with their analog predecessors. Information that was not available in conventional systems can be delivered to the user in a more accurate, precise and reliable form, data can be presented in the specific way it is needed, HSI can be tailored to meet the needs of different users and certain interface management tasks can be automated [13]. With possibilities come, however, also challenges that need to be met in order to develop suitable user interfaces for nuclear power plant control room. Even though there is more data available, the data often doesn't match the information needed [2]: it may be irrelevant for current situation or too low-level [13]. It should be considered thoroughly what kind of data the users need and how it should be presented. There might also be too much information to monitor and detection of meaningful changes may not be salient without alarms, monitoring the big picture may be difficult and information access tasks can be too demanding [13].

In the following sections, ways to overcome the challenges and to get the most out of the opportunities are presented. The goal of these sections is to find some guidelines for representing automation-related information in nuclear power plant control room user interfaces. These guidelines are to be utilized in Section 5 when developing the simulator user interface.

4.1 General principles for good human-automation cooperation

Shortly put, human-automation cooperation aims for optimizing the performance of a human-machine team [2]. Instead of viewing the automation as a tool, the human operators and the automated system are considered a team that works jointly to achieve the operational goal. The term cooperation is used instead of interaction as both parties should actively contribute to team work in order to achieve the common goal. The cooperation ability of automatic systems differs based on their characteristics such as interface design and task allocation. Automatic systems may also have specific modules for supporting cooperation. As there are human operators involved, the cooperation ability can be seen not only as a measurable property of the system but as an attribute based on subjective operator judgements. The operators' perceptions of a system's level of co-operability will reflect their opinion on how well the system facilitates goal achievement and contributes to it.

[29]

Several factors contribute to the success of human-automation cooperation. Considering these factors and their effects on the cooperation, general principles for e.g. interaction between the agents, their roles, required knowledge and reacting to failures have been suggested in the literature. The following summarizes the means for optimal teamwork between human operators and automation based on these suggestions.

Interaction Interaction of the parties (human operators and automation) should be supported [2]. The operators need to be able to redirect the automation [17] but also the automation should be able to model the operators' intentions and actions and react correspondingly [30]. Automation should communicate with the operators [17] and perform the actions requested by them [29]. All team members need to be capable of modifying the other parties' actions and responsive to their influence [30]. The operators' interaction with automation should support their understanding of the automation and maintenance of skills [17].

Roles and responsibilities The relationship between human operator and automatic system will not be symmetric as the operators are ultimately responsible for the performance outcome [29] and the safety of operations [26]. The automatic system is expected to assist the operators [29] but human operators must remain in command of operations [26] and be in charge of the automation [17]. Allowing the operators to actively participate in decision-making processes not only provides safety benefits but promotes situation awareness and enables the joint human-automation system to respond more flexibly to unanticipated events [31]. Automation should conform to the operators' needs rather than require the operators to adapt to it, as well as become more understandable, predictable and sensitive to the operators' needs and knowledge [30]. The purpose of automation should, nevertheless, be well defined [2] and, instead of being left with a pure assisting role, automation should be able to enter in goal negotiations [30]. Well-designed allocation of responsibilities leads to optimized team performance [17].

Mutual knowledge In order to effectively work in a team, the team members should have common ground, that is, shared knowledge, beliefs and assumptions [30]. The operators need to understand the automation's abilities, limitations and goals [17]. The understanding should be supported by the automation making its own targets, states, capacities, intentions, changes and upcoming actions obvious to operators [30] and the HSI representing the function of automation and its interactions with the plant functions, systems and components, as well as providing information to monitor and maintain awareness of the automation's goals, status and other properties [17]. The information that the automatic system provides should be relevant to the situation and the operators should immediately understand the information as well as receive it in time to benefit from it [29]. It is not only the operators who need to understand the automation but the automation should be able to interpret the signals it receives from the operators [30]. Situation awareness should be maintained by both parties [2]. Faulty mutual knowledge has to be repaired when detected [30].

Response to failure Managing failures [2] and preventing breakdowns in team coordination are essential for successful cooperation [30]. Automatic systems should support failure management [17]. Thus, it is important that automation is capable of signalling when it's having trouble and might be unable to participate in an activity [30]. Automation displays should support the operators in determining the locus of failures [17].

Trust In order to rely on automation, the operators need to trust it. Trust guides reliance in particular when complexity and unanticipated situations make a complete understanding of automation difficult [32]. For optimal performance trust needs to be well-calibrated and HSI should support the calibration of trust [17].

Predictability supports the formation of trust. The more autonomy the system possesses, the less predictable it is. This can result in operators not trusting complex automation. In addition to automation being predictable it should also be able to predict the operator as reasonable mutual predictability is needed for optimal teamwork.

[30]

Workload For cooperation to improve performance, the effort needed for the cooperation itself shouldn't be excessive. Workload from secondary tasks related to dealing with automation should be minimized [2, 17]. This can be done by the automation directing the operator's attention to important signals and not overwhelming them with unnecessary information [30].

Skjerve et al. [29] state that the extent to which the quality of human-automation cooperation can be expected to have an effect on the joint human-machine system performance is furthermore questionable. They remind that during normal operation a highly automated system will contribute more to the joint system performance than the operators and thus the impact of co-operability may be only marginal as compared to the impact of the system algorithms and other properties. However, the research in the HACAS project focuses precisely on abnormal incident and accident situations where intensive cooperation between human operators and the automated system may be needed and where lack of it may lead into severe consequences. It should be also noted that some level of cooperation is necessary not only in unanticipated situations but always when there are humans working with automation. Since the cooperation mainly happens through the human-system interface, it again brings us to the importance of good HSI design.

4.2 Guidelines for designing good automation HSIs

Human-system interface is the only boundary between the operators and the system. Every single piece of information from the system to the operators and vice versa is transferred through this interface. Tasks in the interface are performed through dialogues between the user and the system, and the user needs to understand the structure of the interface and learn the appropriate "language" to be able to evoke action sequences related to a task [33]. The structure and the language depend on the selected information visualization technique. As Gilger [34] states, an information visualization approach can either make the operator's work more manageable or it can force the operator to work harder and experience stress during task execution. Remarkable focus should be put on user interface design in order to reach the former.

In digital world the biggest limitations for information visualization are caused by human abilities and complex system properties [34] rather than e.g. the physical layout of the control room. In order to meet the limitations, an information display must be limited in size and contain multiple dimensions of data [34]. Several new user interface design concepts have emerged to answer this need. Among these are for example ecological displays, function-oriented displays, task-based displays and situational displays [13]. The goal of any information visualization concept should be to create an effective format that is easy to interpret and understand [34].

There are few things to consider when developing a visualization technique. The role of any new information display approach needs to be understood within the context of overall information needs of plant personnel and, before introducing a set of new displays, one should think whether the approach effectively adds something to the already information rich control room [13]. Any visualization technique should exploit cognitive strengths where possible and aim for reducing cognitive loading [34]. Not only the contents of the display matter but also the design process of a display should be clear and sufficiently defined [13] in order to maintain the integrity of a control room. Every time when lots of information is presented in a same display the complexity of the display may become an issue. However, the experiment done by Skjerve et al. [21] pointed out that if the operators only need to focus at one particular part of a display at any one time and the parts are not complex, then the overall complexity of the display is not a problem.

What comes to effectively presenting automation in user interfaces, several suggestions for what to present and how have been made. No official and unambiguous guidelines exist but some conclusions can be drawn from literature. The keys to successful presentation seem to be observability and feedback, minimized workload and transparent failure management. The following subsections summarize some design principles leading to optimal results in these fields.

4.2.1 Observability

Observability of an automatic system depends on the amount and nature of feedback provided by the system as well as the means of presenting information. The feedback should give the operators insight into the process the automation is guiding [2] and utilize the human strengths which include our ability to perceive contrast, change and events as well as recognize patterns and react on the basis of this recognition [35]. The information presentation means should be self-descriptive and compatible with the operators' expectations affected by e.g. their general experiences and schooling [10].

For good observability, information about the past, the present and the future should be available. Background information including historical context, data sources, processing, synthesis and effects should be provided [2]. The rules and algorithms used by the automation should be revealed [27] showing how and why the automation arrived at its current state [2]. Showing the target values [11] as well as the automation's contribution to process evolution by delineating the relations between the current process state, the control means and the target state may help the operators in monitoring automatic control performance [2]. Current changes and events should be highlighted [2, 35] and anticipating future changes should be supported by showing what the automation will do next and why [2]. Knowing what to expect and where to look next enables effective observation of events [35].

The operators should be informed of the tasks carried out by the automation by providing relevant feedback [27]. Explicit feedback increases the operators' understanding of automation [21] thus improving also their automation awareness. It should also be possible for the operators to query the automation about the basis of its actions [2].

Skjerve et al. [21] recommend representing the key automatic devices graphically combined into meaningful wholes and integrated into the representation of the process components on the overview display. According to them, information about the balance within and between the circuits should be provided by representing combined information from several automatic devices. At least one permanently available source of information for each type of data that cannot be mapped simply to others should be provided [11]. Information should be provided at various levels: high level for overall status monitoring and lower levels for more detailed interactions [2].

4.2.2 Workload

Providing sufficient observability through feedback without overwhelming the operator is a critical design challenge. Poorly presented or excessive feedback can add to operator workload and diminish the benefits of the automation. In order to understand automation the operators need detailed information regarding its behaviour but too much detail, on the other hand, may overload them. Even if the amount of feedback was adequate it may not be understandable without the proper context, abstraction and integration [18]. The operator workload may increase due to looking for a suitable display, looking for relevant information on that display and trying to understand the meaning of the information. There are several ways to lighten the operators' burden in these tasks.

The workload associated with searching for a display that includes the needed data can be decreased by integrating automation-related information with traditional process displays [18] and with information related to the operators' other activities [2]. HSIs for automation should be well integrated into other control room HSIs and be consistent with their design as, with proper integration of information, the need for transitions between displays and the number of new displays can be reduced [2]. The feedback about the automation's states, actions and intentions should also be presented such that it directs the operators' attention appropriately [17] in order to avoid unnecessary browsing of displays. Hierarchical presentation of information is recommended by O'Hara and Higgins [2]. They recommend providing displays at various levels of abstraction from top-level overview displays to detailed displays and suggest using navigation aids to enable moving easily from higher level displays to lower level. According to Helldin and Falkman [27], even fully automatic updating of the individual and team situational pictures can be used. They suggest distributing relevant information automatically within the team. The automatic distributing of information should, however, not distract the operators from what they are currently doing. Bainbridge [11] states that the operators should not have to page between displays to obtain information about abnormal states nor information needed within one decision process. The search time for finding the data necessary for making a decision should be reduced also according to Gilger [34].

What comes to easily finding the correct information on a display and understanding it, the most recommended way seems to be grouping related information together and organizing it into meaningful patterns. Pattern-based representations enable the operators to quickly scan through displays and pick up information without complex cognitive work [35]. Gilger [34] states that if the data is represented with specific patterns, shapes and colours that can be imprinted in the memory the operator can process the significance of items subconsciously. According to him, by decreasing the need for complicated interpretation of data when acquiring it, the conscious thinking capacity of the operator can be used for actually understanding the data and its meaning. Combining low-level data into meaningful information can help the operators understand automation behaviour [18] but access to raw data as such has been considered unnecessary as it only overloads the operators with too much information [27]. It should be noted that this result emerged in the fighter aircraft domain where the pace of events is probably faster than in process industry, so opposite opinions can also be expressed. When aiming for ultimate safety no opportunities for missing critical information due to filtering data should exist. Bainbridge [11] proposes an interesting way of reducing workload associated to information gathering by using displays compatible with the specific knowledge and cognitive processes being used in a task. She suggests for example displaying only data relevant to a particular mode of operation or creating displays compatible with different types of operator skill. In these kind of solutions there is, however, always the risk of limiting the operators' options too much.

Providing feedback through sensory channels that aren't otherwise used has also been suggested. Haptic feedback has been promising [18] and verbal feedback proved efficient in the experiment run by Skjerve et al. [21]. The detail possible in visual displays cannot, however, be acquired through other senses [18].

4.2.3 Failure management

Malfunctions in both the process and the automatic system controlling it can cause severe problems if left unattended. In order to avoid this, the HSI should support effective failure management. Automation degradations may be difficult to handle as it is the same degraded automation that ought to signal the operators about the trouble it's having. This signalling is, however, considered to be of utmost importance by many experts in the field of human-centred automation. With increasing automation, attention should also be placed on handling the process malfunctions as they may not be as obvious to the operators as under manual control.

According to O'Hara et al. [15], indications are needed to support the operators' awareness of degraded components within complex systems. They recommend assessing the outcome of instrumentation and control system failures on the HSIs. The functions and systems that are no longer automated due to degradations should be explicitly presented to the operators [27]. Skjerve et al. [21] state that explicit graphical representation of key automatic devices combined with verbal feedback about the activities of the devices efficiently supports the operators' ability to handle automatic malfunctions. For minimizing the issues caused by potential malfunctions, it is important both to be able to anticipate the failures and, if not possible to prevent them, locate their sources. O'Hara and Higgins [2] advice to support the anticipation of failure and to show the reasons for automation failures that have occurred or are about to occur. According to Helldin and Falkman [27], to support the anticipation, the operators should be signalled when the automation is progressing towards its limits. They suggest providing means to indicate that data used by the automatic system is missing, incomplete, unreliable or invalid and, if the automation is used for decision-making and evaluating the situation, presenting the reliability of the results to the operators. Also the sources of automation failure should be revealed [27].

Even if the automation is functioning correctly it might prevent the operators from noticing failures in the process. Bainbridge [11] notes that automatic control can camouflage system failure by controlling against variable changes so that the trends don't become apparent until they are beyond control. According to her, this could be prevented if the automation would also monitor unusual variable movement and react accordingly. Different types of alarms are commonly used in nuclear power plant control rooms to indicate deviation in normal process functions. As stated by Bainbridge, alarms are, indeed, necessary for the operator to quickly notice a low probability event. However, an abundance of flashing red lights will confuse the operator rather than help [11], so careful planning is needed for efficient alarm system design.

5 Developing the simulator environment

The practical goal of this thesis was to design and develop a user interface for a simulator environment that is to be used for automation awareness related studies in the future. The scope of the simulator is the emergency diesel power generation system, and the emergency diesel system of Loviisa nuclear power plant was used as a reference system for the simulator. The user interface should support the development and maintenance of the operators' automation awareness, which is accomplished by utilizing the theory discussed in previous sections and especially the guidelines in Section 4.2. This section first presents the tools and the reference system used for the development of the simulator environment and then goes through the design process of the user interface step-by-step.

5.1 Tools

The user interface for the simulator environment was developed with ProcSee. ProcSee is a user interface management system developed in OECD Halden Reactor Project and is used for developing graphical user interfaces (GUIs). ProcSee is the third generation of the Picasso/ProcSee project that has been on-going for over 20 years [36]. ProcSee was selected as a tool for developing the user interface as it has been successfully used in VTT for similar projects and is designed to work well together with the modelling software Apros that is used for developing the simulation model. Some advantages of ProcSee include an interactive graphics editor that can be used for testing the dynamic behaviour of the user interface and the ability to modify the GUI at run-time [36].

Apros (Advanced Process Simulation Software) is a simulation software product developed by VTT and Fortum. Apros can be used for full-scale modelling and dynamic simulation of industrial processes such as combustion power plants, nuclear power plants and pulp and paper mills [37]. For the development of the automation awareness simulator environment, a ready-made Apros model for Loviisa nuclear power plant was used.

Microsoft Excel was used for creating the initial drafts for the user interface displays.

5.2 Scope and reference system

The scope of the simulator had been selected in cooperation with Fortum already before starting the thesis. The emergency diesel power generation system was selected as it is quite a separate process and could be viewed without a deep understanding of the whole nuclear power plant. The emergency diesel system of Loviisa nuclear power plant was used as the reference system for the simulator.

The purpose of the emergency diesel power generation system is to automatically ensure the power supply to safety-critical systems and devices in case of a failure in normal power supply. Both plant units in Loviisa nuclear power plant have an emergency power plant consisting of four diesel generators, two for each redundancy.

The user interface of the simulator environment has been developed for the first generator in the first redundancy.

5.3 Design process

As it was not possible to carry out a full-scale design process within the limits of the master's thesis, a lighter approach to design was adopted. The design process used to produce the user interface follows loosely the ideas of the process model of user-centred design introduced by Jokela [38], illustrated in Figure 5. The steps of the design and development process of the user interface are further discussed in sections 5.3.1 - 5.3.4.

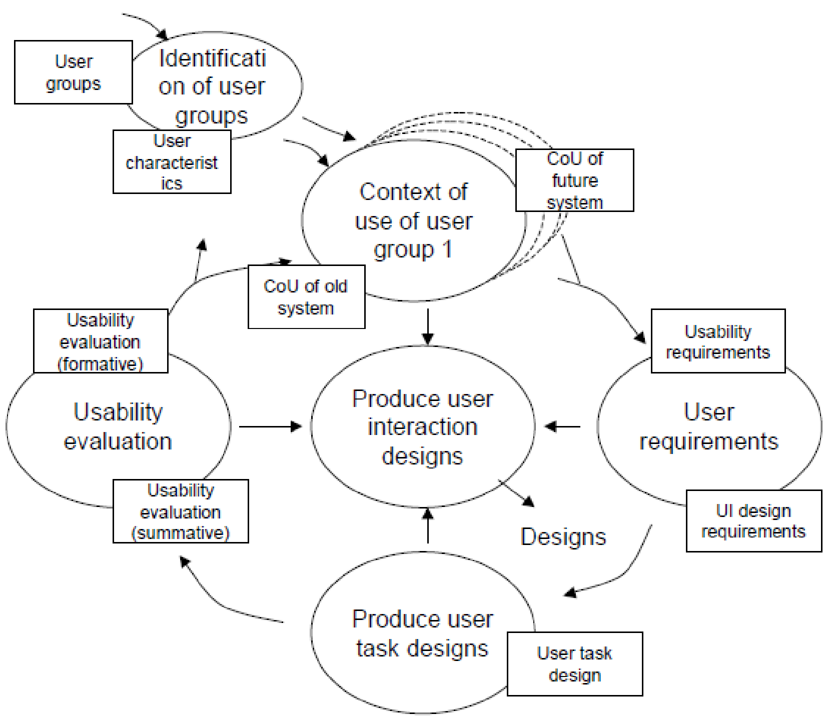

Figure 5: The process model of user-centred design [38]. The model is based on the standards ISO 13407 and ISO 18529.

5.3.1 Defining context of use and requirements

The first steps of the process model by Jokela include identification of user groups and defining the context of use for each group [38]. Within the automation awareness simulator case not much effort was put on defining the user groups and characteristics, as it was considered more important to produce the user interaction designs and user task designs. These steps of the process model include designing the actual information presentation means and functions of the user interface and contribute thus more to the development of the simulator environment. Ideally, a thorough research on the user groups would have been made, but as the simulator is known to be used by professional control room operators of a nuclear power plant, existing knowledge of the characteristics of that user group can be utilized. Defining the context of use for the simulator user interface was slightly harder as two different viewpoints needed to be taken into account. On the other hand, the actual use of the emergency diesel system itself and tasks related to operating the system were thought about. On the other hand, the user interface under development should support performing tasks related to the automation awareness studies that will be executed in the future. As the study cases haven't yet been planned, defining the context of use done within the master's thesis concentrated on the actual use of the emergency diesel system rather than the future simulator studies. Based on discussions with representatives from Fortum and a modelling expert from VTT, it was decided that the focus of the simulator will be on the periodic testing procedure (koestus) of the diesel system as that offers the most versatile options for the test scenarios. Also normal operation of the system is enabled by the developed user interface.

The next step of the process model is defining usability and user interface design requirements for the product [38]. For this, the guidelines in Section 4.2, along with background material from Fortum, were utilized. As the goal of the user interface is to support the operators in understanding the automation more deeply, a basic requirement for the user interface was to provide some information related to the automatic functions of the emergency diesel system. The question of *what* to present was addressed by viewing the draft displays for the new qualified display system user interface of Loviisa nuclear power plant emergency diesel system as well as the user guide and testing guide of the old emergency diesel system. Based on this material, a list of needed information was created. Then, the guidelines defined in Section 4.2 were used to decide *how* to present the information. Particularly the following guidelines were considered as key requirements for the user interface:

- Create an effective format that is easy to interpret and understand, use self-descriptive information presentation means
- Exploit cognitive strengths and reduce cognitive loading, utilize human strengths such as perceiving change and recognizing patterns
  - Group related information together and organize it into meaningful patterns
  - Represent data with specific patterns, shapes and colours
- Provide information at various levels (hierarchical presentation of information)
- Provide information needed within one decision process on one display

Not much information was available about the structure and functions of the new automation related to the emergency diesel system, so displays specific to automation were not designed. As integrating automation information into process displays is widely recommended, this wasn't seen as a problem but it was decided that actions of the automation controlling the process will be displayed among the process information.

5.3.2 Initial design

The actual design process (loosely mapped to steps 4 and 5 of the process model in Figure 5) of the displays started with going through the background material which included the draft displays for the new qualified display system user interface of Loviisa nuclear power plant emergency diesel system as well as the user guide and testing guide of the old emergency diesel system. Based on this material, five key displays were selected for development and drafts for these were created in Microsoft Excel. MS Excel was selected as a design tool for the first drafts, as testing the concept and ideas of information presentation methods was considered lighter with it than with ProcSee. As no clear vision of the user interface existed at this point, it was important to be able to modify the drafts easily, which was enabled by MS Excel. Three of the selected displays are process displays presenting the functions, parameters and controls related to the process. The two other displays are logic displays presenting the system status. After user evaluation (discussed in more detail in the following section) a third logic display was added. As the language used in the Loviisa nuclear power plant control room user interfaces is Finnish, also the simulator user interface is in Finnish. Thus, translations of the display names and of some key components on the displays are provided. The selected six displays are the following:

- Main display (Päänäyttö)

  The main display includes the control buttons for running and testing the diesel generator, as well as information on key parameters of the generator such as power and voltage. In addition to the information related to the generator itself, the main display provides insight to some other process components such as pumps and cooling fans. Also some alarms are presented on the main display.

- Subsystem display (Apujärjestelmät)

  The subsystem display covers the subsystems such as sea water, jacket water and lube oil. The display includes control buttons for pumps and starting air compressor as well as information on the key parameters of the subsystems. Also some generator parameters are displayed.

- Air-conditioning display (Ilmastointi)

  The air-conditioning display includes control buttons for fans and information on the temperatures inside the diesel room and the diesel control room along with the outside temperature.

- Ready-for-starting display (Käyntivalmius)

The ready-for-starting display represents the logic to determine if the diesel generator is ready for starting or not and why.

- Fault display (Häiriö)

  The fault display represents the logic to determine if a fault exists and why.

- Trip display (Laukaisu)

  The trip display represents the logic to determine if a diesel generator trip has been triggered and why.

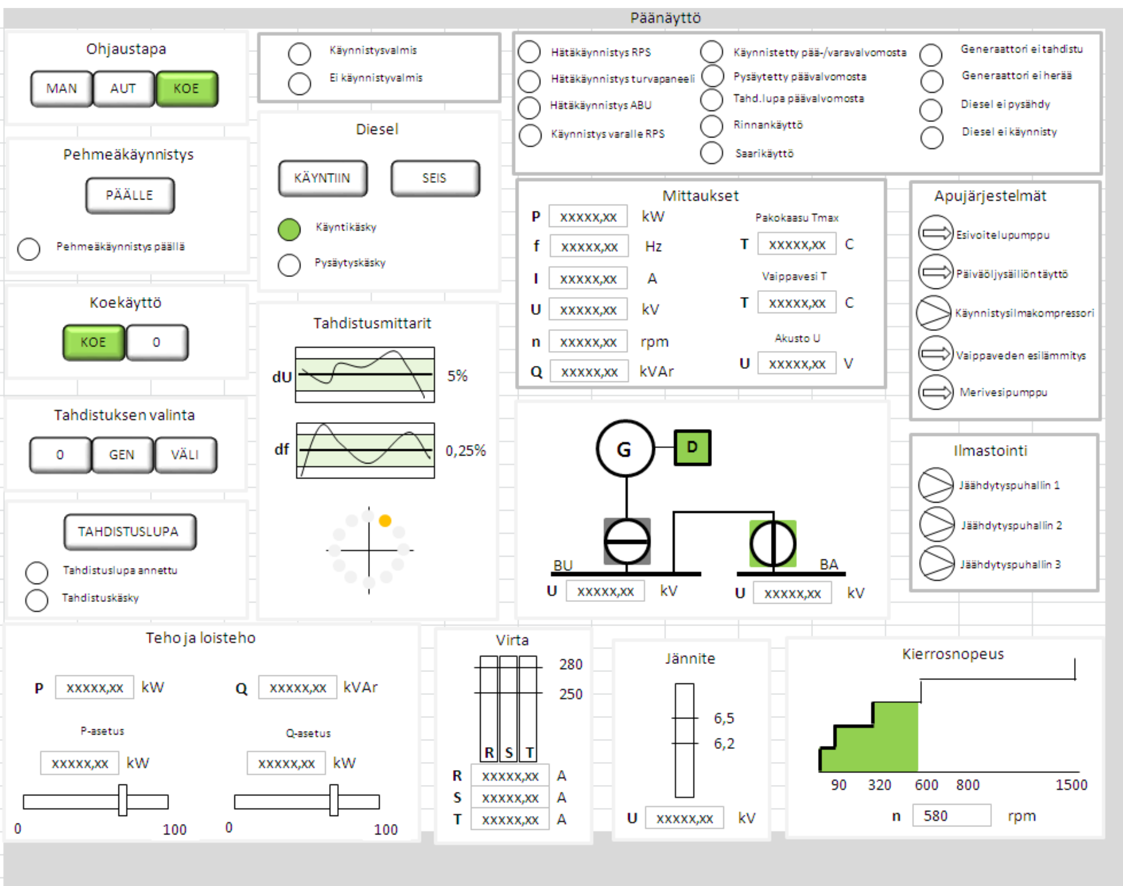

Figure 6: The first draft of the main display.

The first drafts of the main display, the subsystem display and the air-conditioning display are presented in figures 6 - 8 consequently. The initial design of the process displays aimed for combining related information together and representing the key parameters graphically. Each display is divided into separate sections with frames around the user interface components to make them easier to read and to aid focusing on a particular section of the display at a time. The graphical representation of

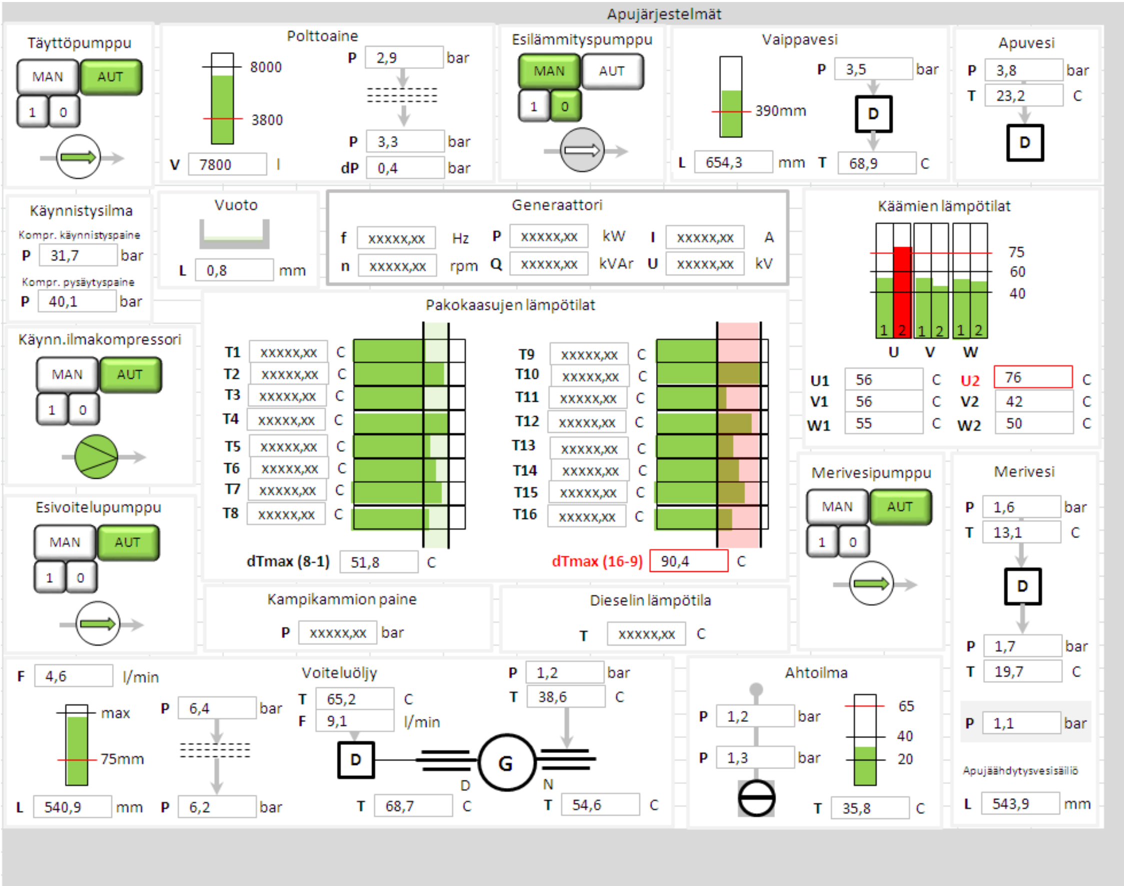

Figure 7: The first draft of the subsystem display.

the changing system parameters reduces cognitive loading as only a quick look on the display is required to determine if the parameter values are within normal limits or not. It is also easy to perceive change from the graphical parameter representations.

For each logic display, drafts representing the different system states were created. The drafts for the ready-for-starting display are presented in figures 9, 10 and 11. In Figure 9, a case where the diesel generator is ready for starting is presented. The running status of the diesel generator is presented on the left, possible issues that prevent the diesel from starting are presented in the middle and the indication for if the diesel generator is ready for starting or not is presented on the right. Figure 10 presents a case where the diesel generator is already running and Figure 11 a case where the diesel generator is not ready for starting as there is a fault.

Fault display drafts are displayed in Figures 12 and 13. Figure 12 presents a case where there is no fault and 13 presents a case where a fault exists. The potential issues are presented on the left and the fault status on the right.

As the trip display was added to the design later, there is no proper initial draft of it. The final version of the display is presented in Section 5.3.4 among other displays in the final user interface.

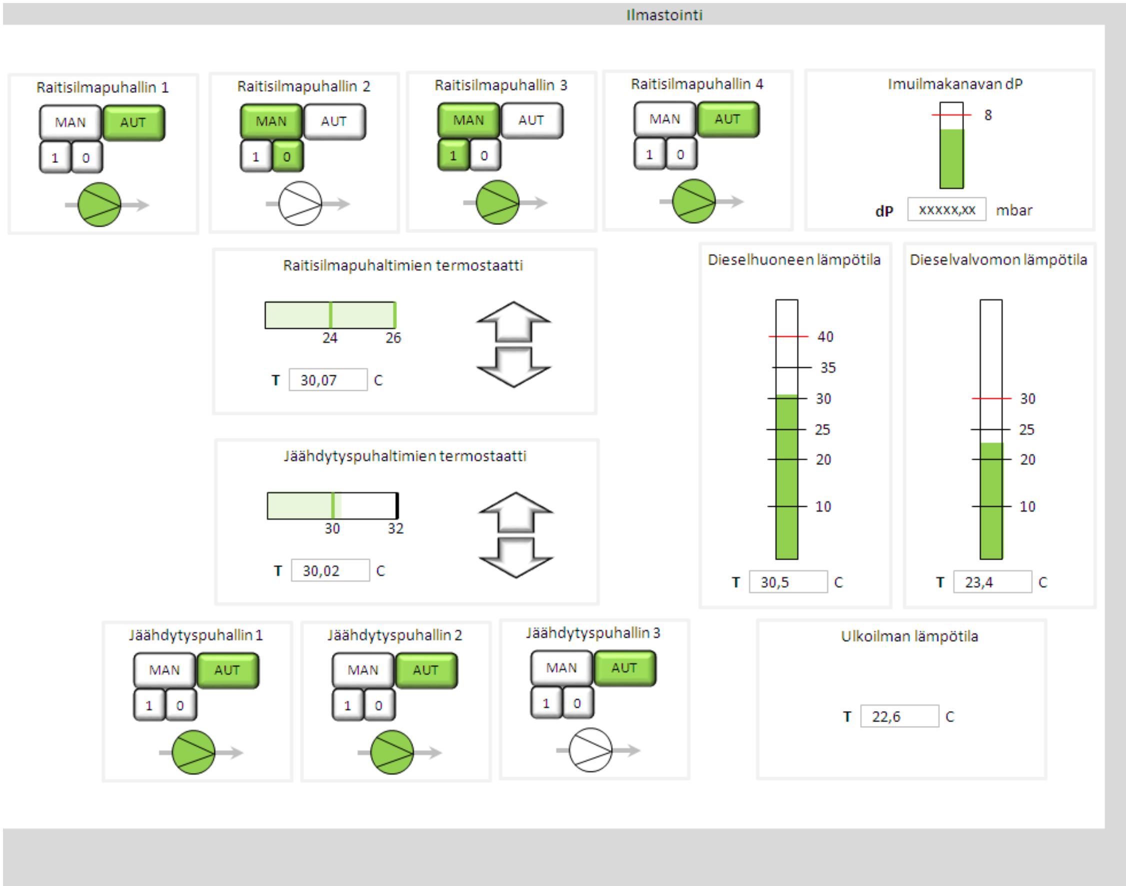

Figure 8: The first draft of the air-conditioning display.

5.3.3 Evaluation of initial design

The draft displays were evaluated with a group of Loviisa nuclear power plant operators as a part of a training on automation competence in digital control rooms organized by VTT. The group consisted of eight operators with varying backgrounds and operator roles. The operators were divided into three smaller groups, each of which was lead by a VTT representative. The groups discussed on the display design based on a ready-made set of questions. As the displays under evaluation were only initial drafts, the discussion concentrated more on the selected information presentation methods and concepts than the contents of the displays in detail. The question set used in the discussions consisted of questions related to the displays in general as well as questions specific to each display. Questions specific to each display were divided into questions considering the selected information presentation ways and questions testing the operators' understanding of the display. The discussion was held in Finnish and the original questions in Finnish are presented in Appendix A. The English translation of the questions is presented below.

1. General questions

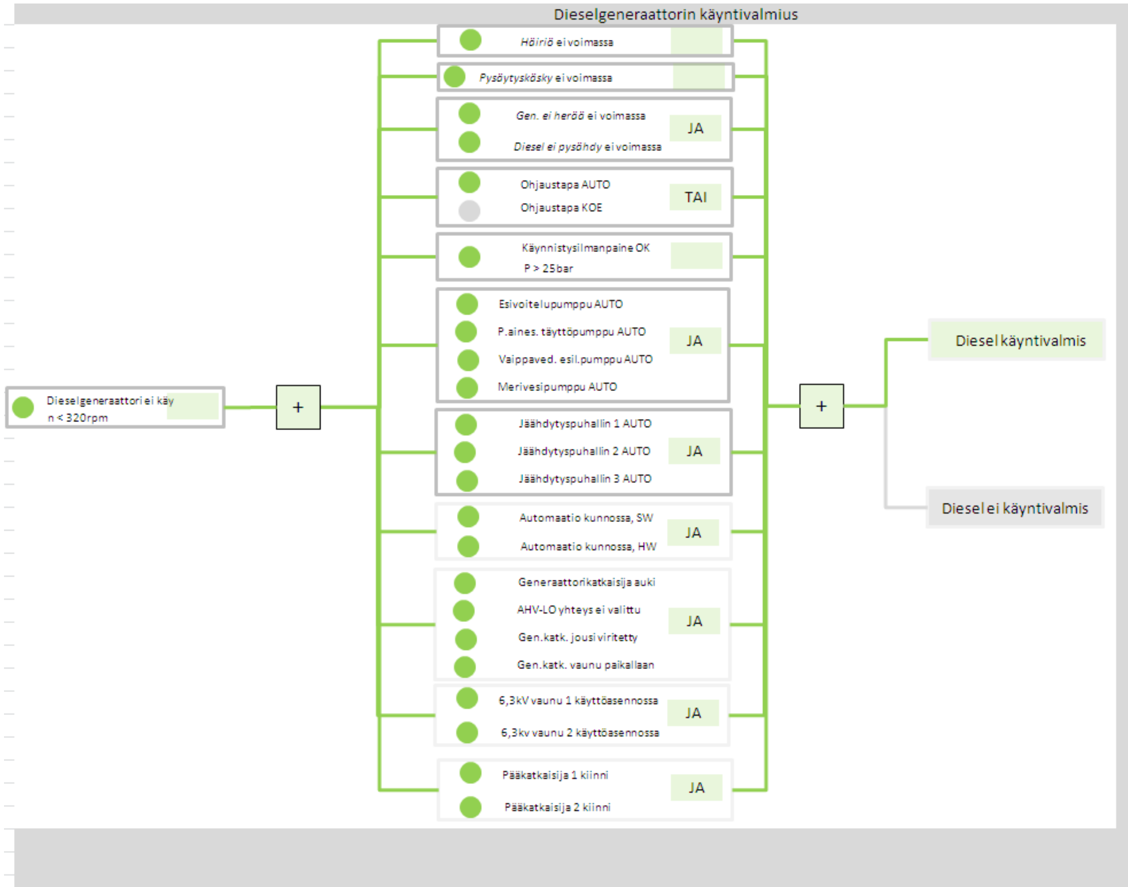

Figure 9: The first draft of the ready-for-starting display, case A (diesel generator ready for starting).

(a) Do the displays include all necessary information for testing/using the emergency diesel system (excluding trends and alarms)?

(b) Is the information divided reasonably between the displays?

(c) Is the information grouped reasonably on the displays?

(d) Do the displays include irrelevant information?

(e) Do the displays employ methods of information presentation you don't understand?

2. Main display

(a) Rotation speed: does the step-like representation make it easier to perceive the phases of diesel start-up (90 rpm - engine starts, 320 rpm - sea water pump starts, 600-800 rpm generator starts, 1500 rpm - diesel running with no load)?

(b) Power and reactive power: is a slider a suitable tool for setting the power value? Is it useful to be able to set the value by writing?

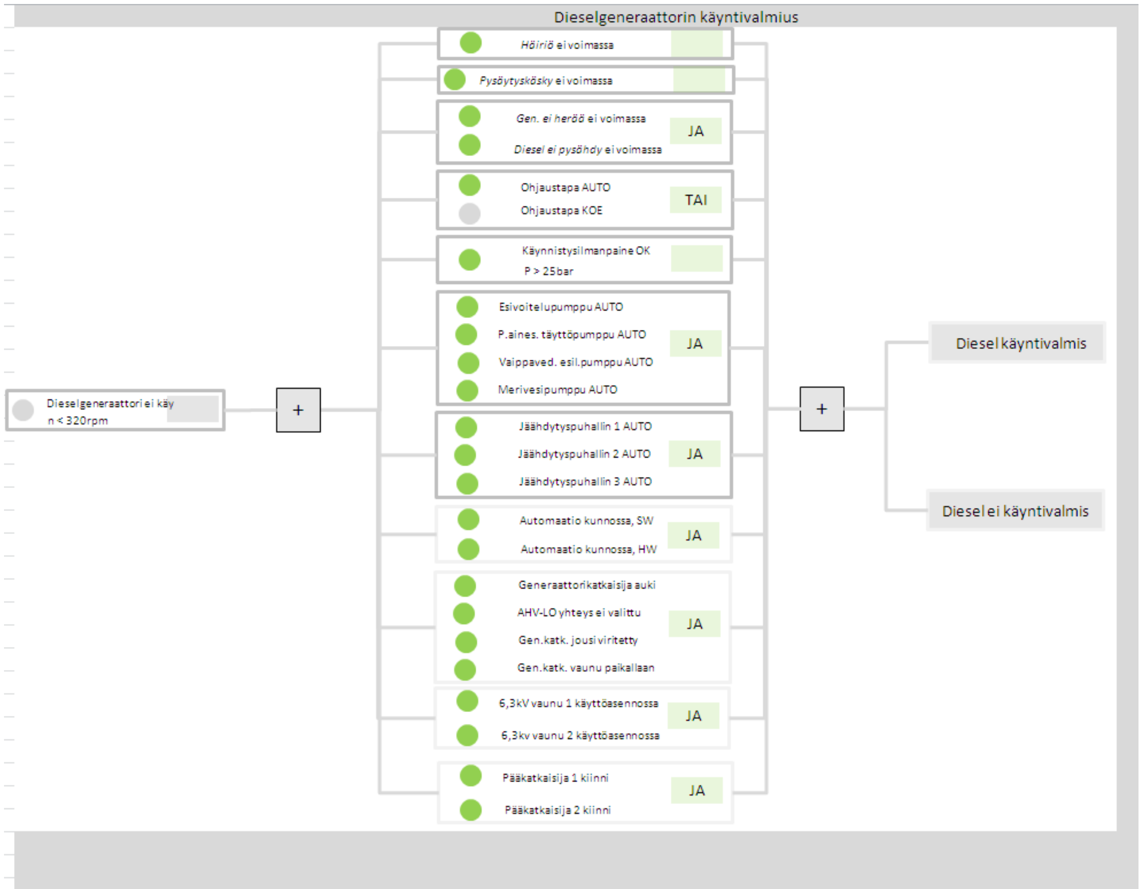

Figure 10: The first draft of the ready-for-starting display, case B (diesel generator running).

   (c) Synchronizing meters: is the representation clear? Is it useful to see the information during automatic synchronizing?
   (d) Current: is it useful to be able to compare the currents?
   (e) Would it be useful to represent some other parameters graphically? If yes, what?
   (f) On which position is the operational switch?
   (g) What is the current rotation speed and what does it mean regarding the diesel start-up status?
   (h) Have any alarms been triggered?

3. Subsystem display
   (a) Exhaust gas temperature difference: is the representation clear?
   (b) Coil temperatures: is it useful to be able to compare temperatures?

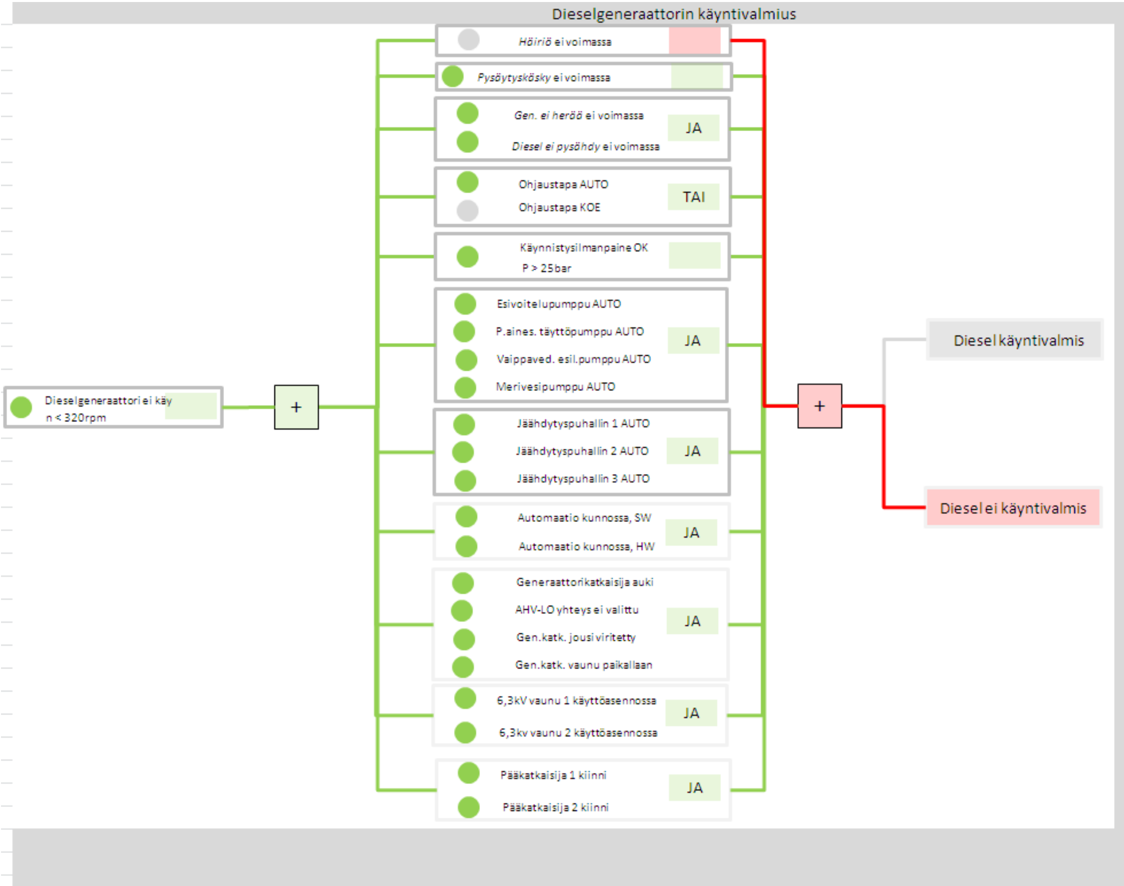

Figure 11: The first draft of the ready-for-starting display, case C (diesel generator not ready for starting).

   (c) Arrangement of measurements and control buttons: are the separate entities understandable (pumps combined with control buttons, measurements “split”) or should the arrangement follow reality?
   (d) What is the maximum temperature difference between the cylinders 8-1?
   (e) Which pumps are running? How are they operated?
   (f) What is temperature of lube oil before the engine? What about before N-bearing?
   (g) Have any alarms been triggered?

4. Air-conditioning display
   (a) Which fans should be running based on thermostat temperatures (30 C - cooling fans 1 and 2, 32 C - cooling fan 3 — 24 C - fresh air fans 1 and 2, 26 C fresh air fans 3 and 4)? Are they? (Why not?)
   (b) Is the diesel control room temperature higher or lower than the temperature outside?

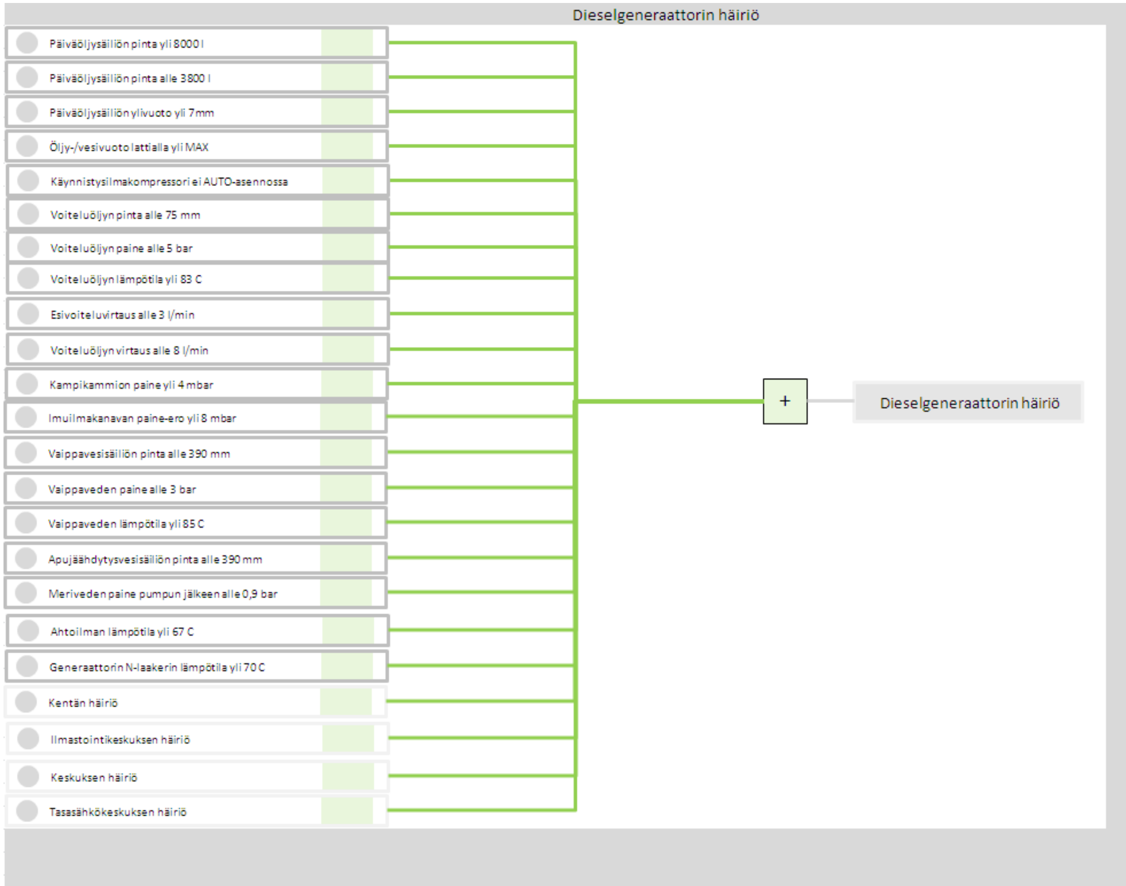

Figure 12: The first draft of the fault display, case A (no fault).

5. Ready-for-starting display
   (a) Cases A-D: Is diesel generator ready for starting? (Why not?)
   (b) What would the display look like if the operational switch wouldn't be on AUTO position nor on KOE (test) position?
6. Fault display
   (a) Cases A-D: Is there a fault? (Why?)

In addition to answering the questions the operators were able to bring out their general thoughts of the displays during the discussion. The discussions were recorded and the recordings were transcribed and analysed afterwards. Based on the analysis, a set of change requests to the displays was gathered. Each change request was given a priority class based on the significance of the finding and the number of operator groups bringing out the same finding. The findings are classified into errors, issues and suggestions. The difference between an issue and a suggestion is that an issue is an existing design solution that is considered bad by the users whereas a suggestion is a feature that the users think could make the design solution

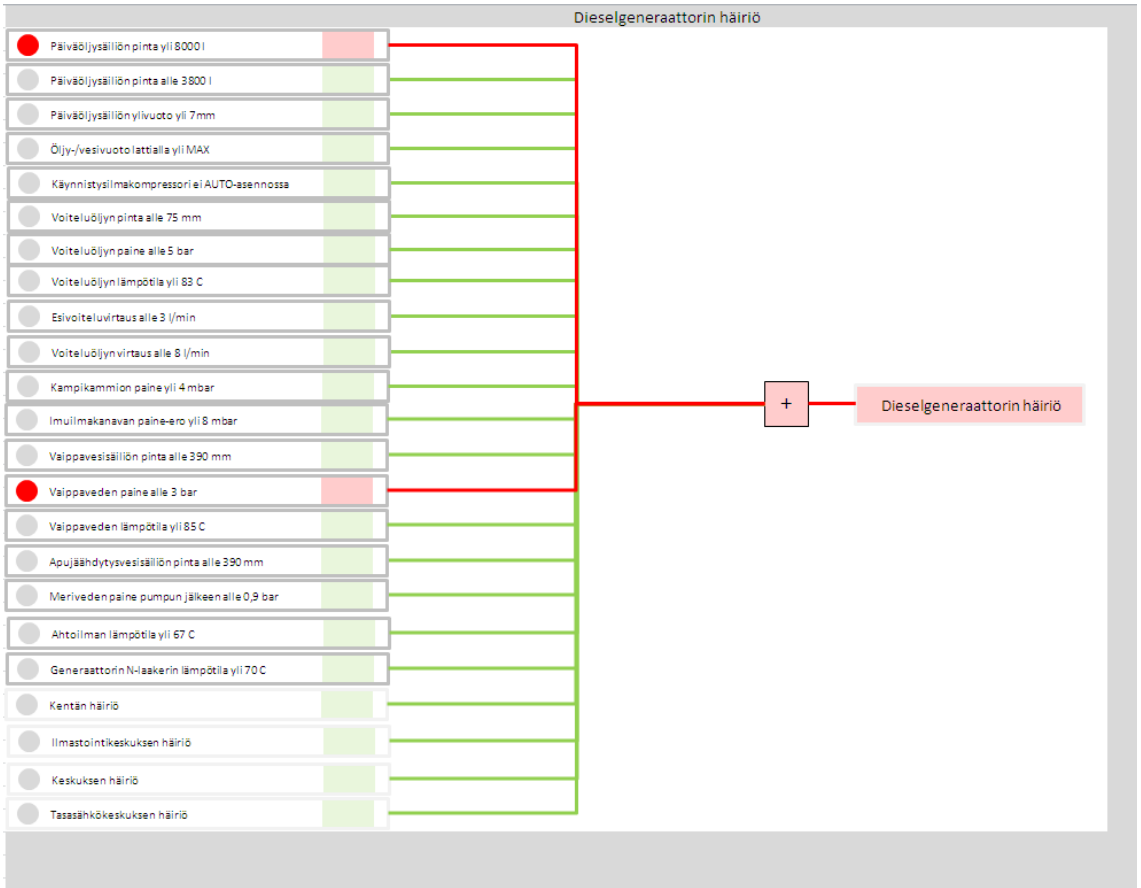

Figure 13: The first draft of the fault display, case B (fault).

better if realized. The relevance of some user findings was uncertain, so they were given their own class "to be checked". The priority classes are the following:

- 1 - Error

  A clear design error brought out by one or several operator groups.

- 2 - Significant issue

  An issue brought out by several operator groups.

- 3 - Issue

  An issue brought out by one operator group.

- 4 - Significant suggestion

  A suggestion brought out by several operator groups.

- 5 - Suggestion

  A suggestion brought out by one operator group.

- 0 - To be checked.

  A finding which relevance needs to be checked from the reference material.

Each change request was mapped to one or several of the guidelines defined in Section 4.2. The change requests related to representing data are mapped to observability, the requests related to finding information and interacting with the system are mapped to workload and the requests related to abnormalities in the system are mapped to failure management. Altogether 33 change requests related to observability, 13 requests related to workload and 2 requests related to failure management were found.

For each accepted change request a design suggestion was made and taken into account when making the final design. The realized changes to displays differ slightly from the initial suggestions due to more careful consideration done in the development phase and the characteristics of ProcSee. The realized design solutions are presented in Section 5.3.4 separately for each display.

The original user findings in Finnish, as well as the change requests and their priority classes and related design guidelines, along with the design suggestions are presented in Appendix B. In addition to the accepted change requests a couple of findings were rejected. The rejected findings and reasons for rejection are presented in Appendix C.

5.3.4 Final design

For creating the final user interface, the results of the user evaluation were analysed and changes to displays were made accordingly. In addition to the three process displays and three logic displays, a menu display and a guide display were added. A navigation bar was added to the bottom of the window. The overall structure of the user interface is presented in Figure 14. The displays are connected with arrows that represent the navigations between the displays. The bold black arrows represent navigation through the menu display, the narrow black arrows represent navigation through the navigation bar and the narrow grey arrows represent navigation through navigation aids on an individual display. If there are multiple navigations between two displays, only the "strongest" navigation is displayed. Navigation to the guide display through the navigation bar is not visualized.

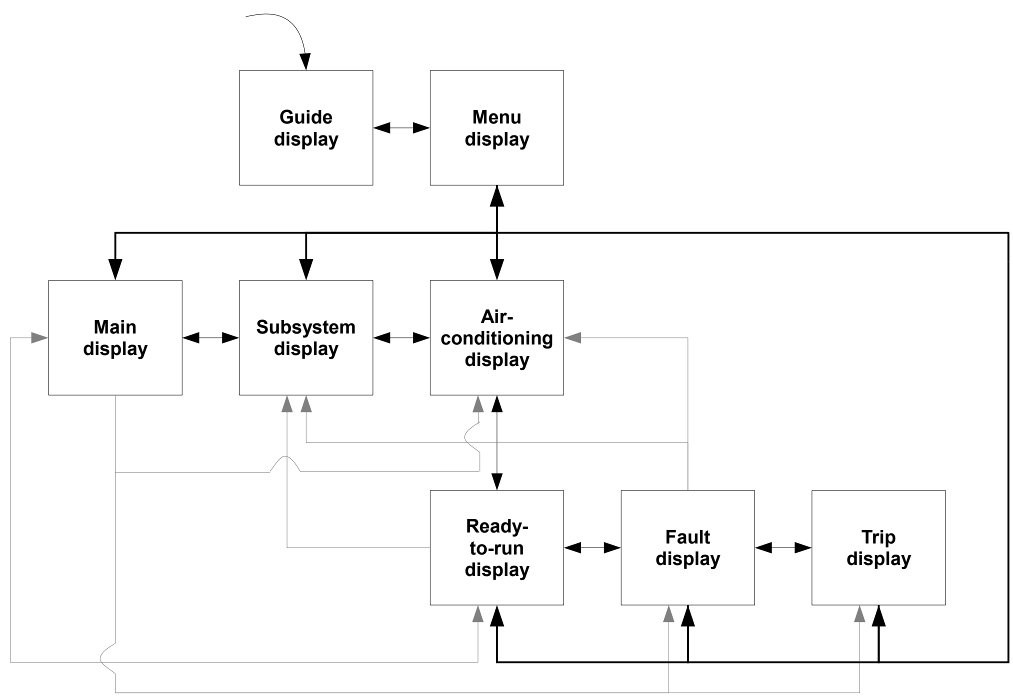

Figure 14: The structure of the user interface.

Next, the final design for each display in the user interface is presented.

Guide display and navigation bar

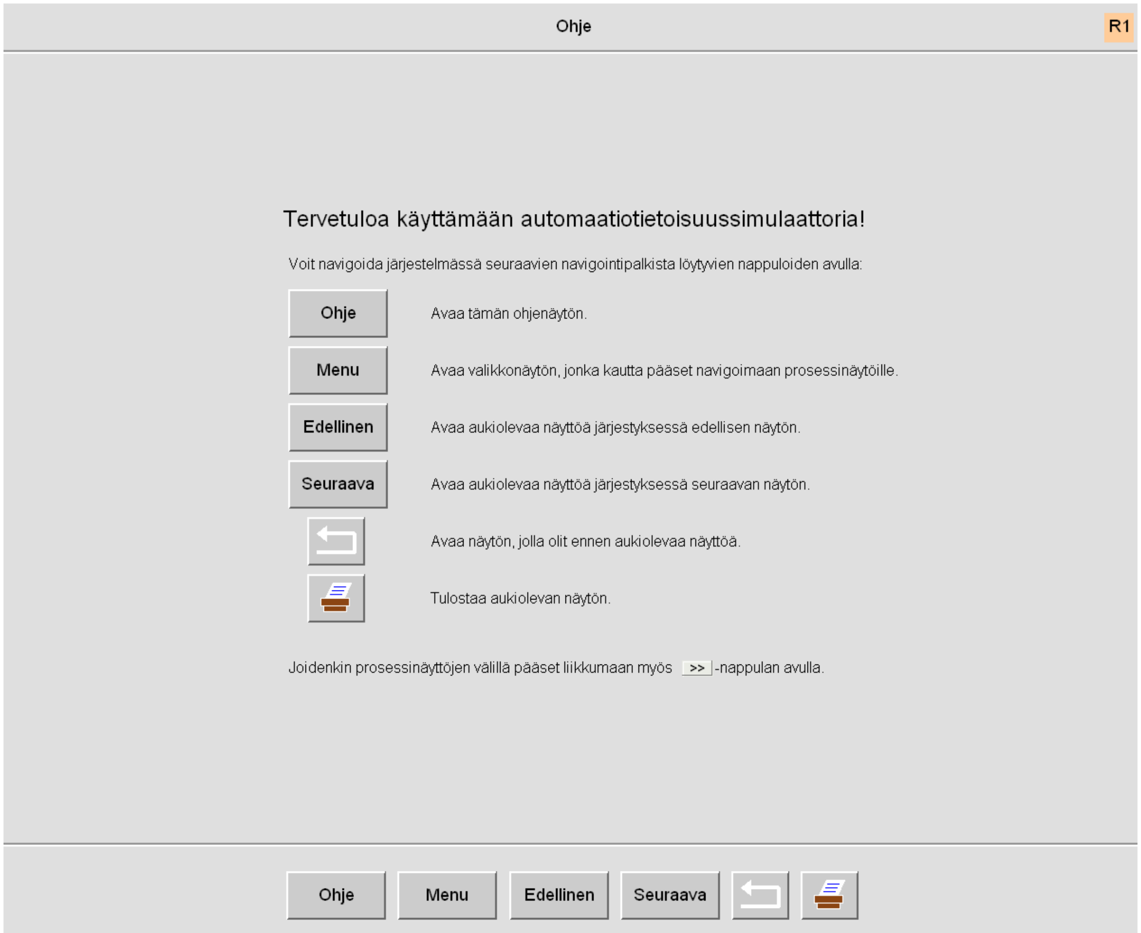

Figure 15: The final version of the guide display.

The guide display is the first display to open when the simulator application is started. It presents the buttons that can be used to navigate between the displays. The menu button takes the user to the menu display, through which it is possible to navigate to all process and logic displays. The buttons Edellinen (Previous) and Seuraava (Next) take the user to the display previous/next to the current display in the pre-defined display order. The button with a white arrow takes the user back to the display they were viewing before the current display. The button with a printer symbol can be used for printing the current display. Figure 15 presents the guide display. The navigation bar can be seen in the bottom of the figure.

Menu display

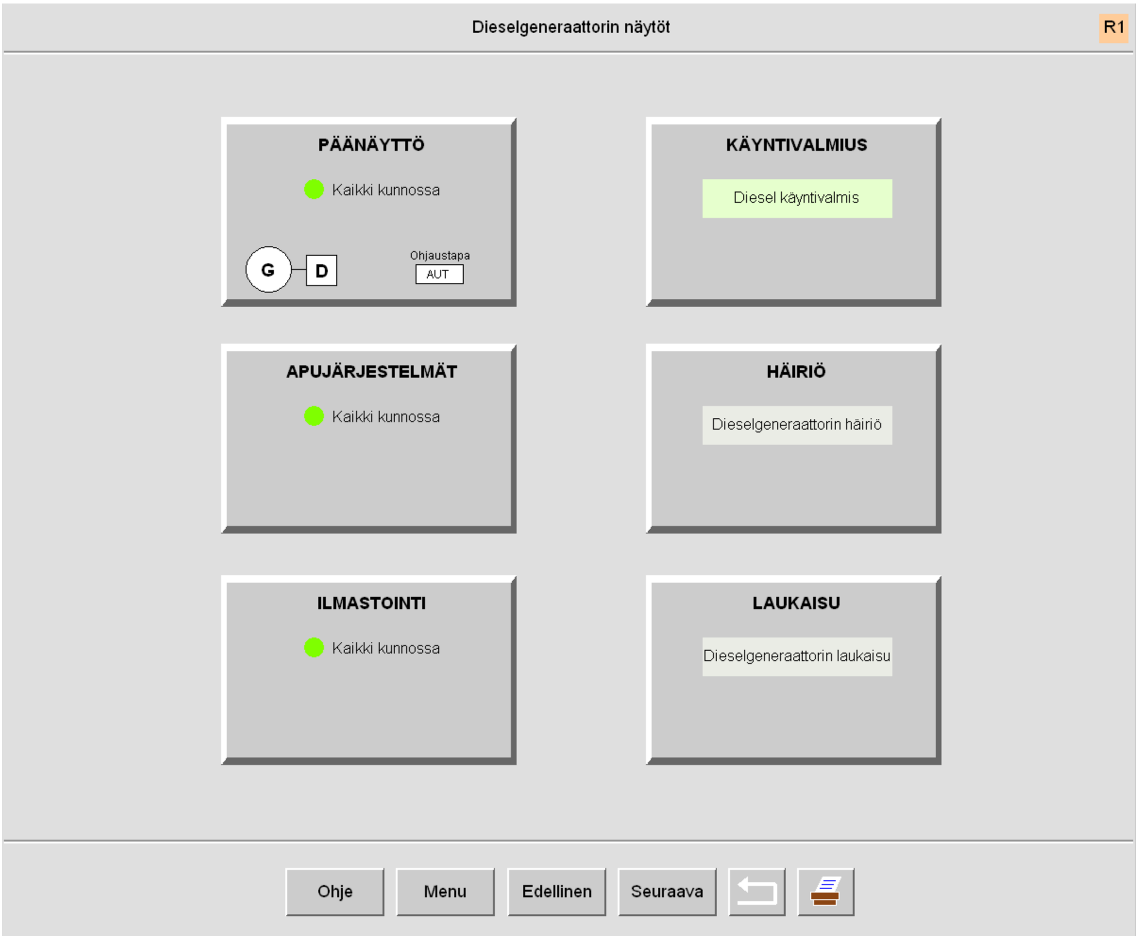

Figure 16: The final version of the menu display, case A (everything OK).

The menu display includes navigation buttons for each process and logic display. As hierarchical presentation of information is considered good for the development and maintenance of automation awareness, the menu display doesn't provide only navigations to other displays but also an overview of the system status. Each navigation button includes information on the related display status and, in case of the main display, on some key parameters of the display. Figure 16 presents the menu display when everything is OK on all displays, and the diesel generator is under automatic operation and not running. If there is something wrong on a process display, the corresponding navigation button displays a text to indicate the fault with the highest priority in addition to display status. Figure 17 presents the menu display when there are alarms on the subsystem display, the diesel generator is not ready for starting and a fault exists.

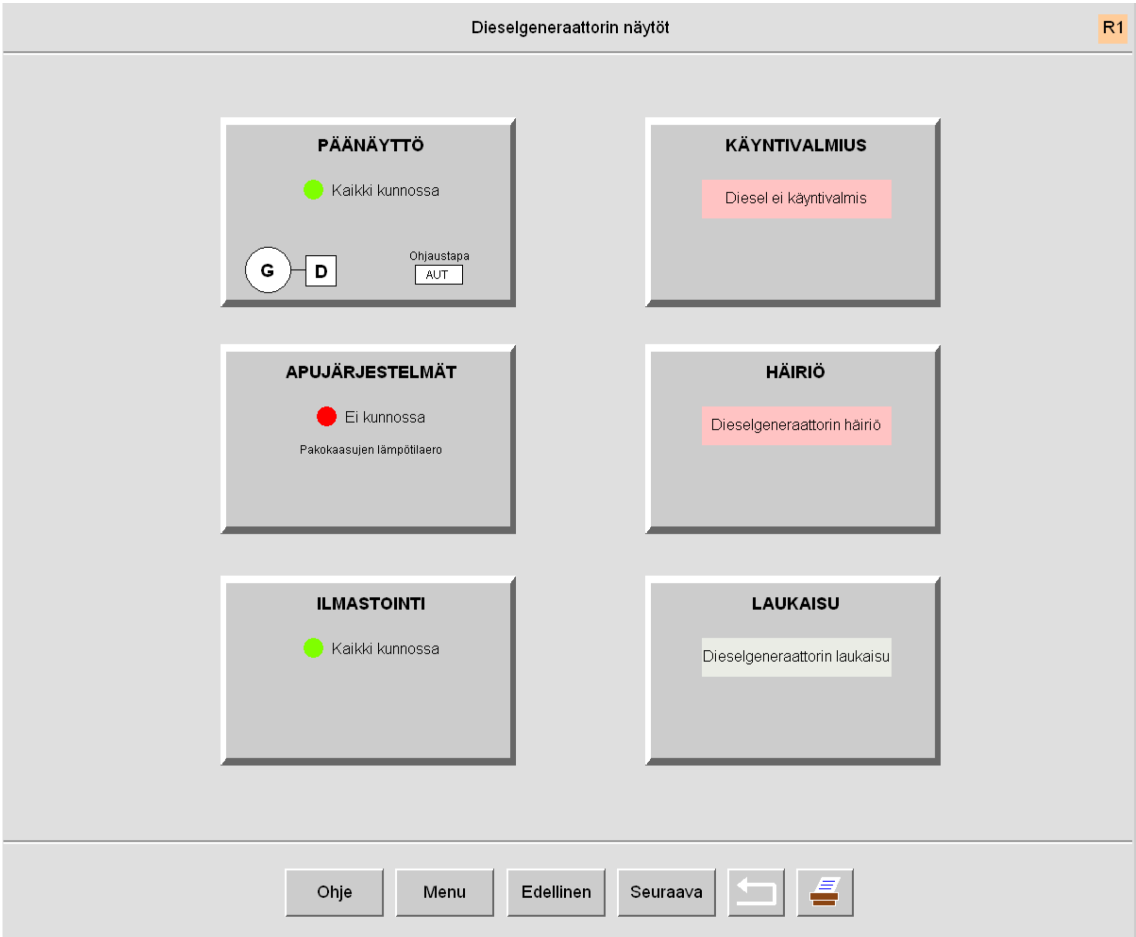

Figure 17: The final version of the menu display, case B (malfunctions on some displays).

Main display

The main display is a general display that includes the information needed for operating the emergency diesel system if everything goes as expected. The focus of the display is on the diesel generator itself, and controls and measurements related to the generator are presented. In addition to that, the display includes some information on the subsystems and air-conditioning, as well as some alarms and information on the system status, combined with navigations to related displays. If a malfunction of some kind is indicated by these, the user can navigate to the corresponding display in order to find out more about the malfunction. Changes to the display layout and graphical representations were made based on the user evaluation. The change requests and realized design changes related to the main display are presented in Table 2. The final version of the main display is presented in Figure 18.

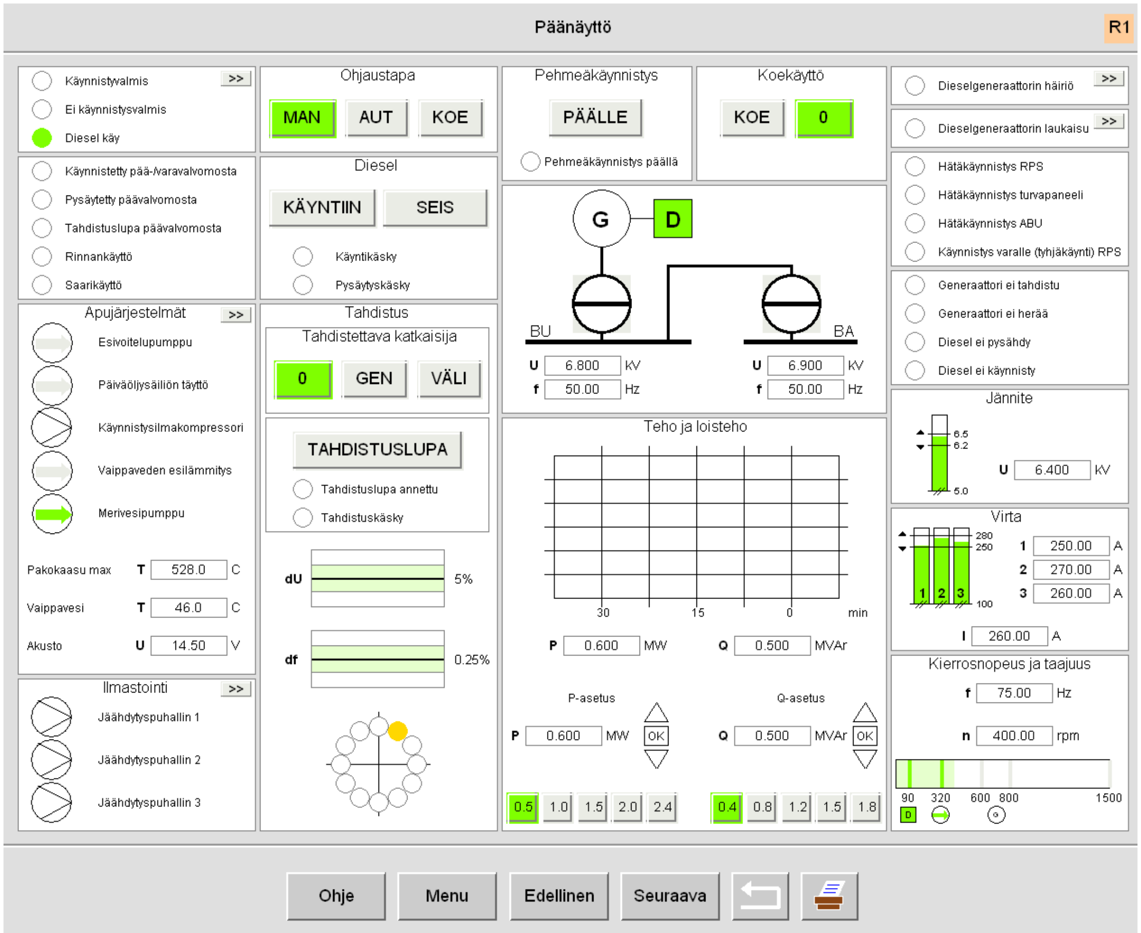

Figure 18: The final version of the main display.

Table 2: Realized design changes for main display.

ID	Change request	Related guidelines	Realized design
3	Rotation speed shouldn't be represented with a step-like diagram. Rotation speed reaches its highest value (1500 rpm) in seconds and stays constant after that. If processes that are initiated during each speed step are to be followed they need to be represented next to the diagram.	Observability	Rotation speed diagram was changed into bar form instead of a step-like diagram. Lines to indicate the steps were added and small symbols for diesel engine, sea water pump and generator were added to make it easier to observe their state during the diesel generator start-up.

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ID	Change request	Related guidelines	Realized design
4	Power and reactive power can't be set with a slider. Actual kW values should be used instead of percentage values. Execution button is needed for starting the power set-up. Possibility for setting the numerical value is needed, tenfold errors should be avoided.	Workload	Slider was removed and selection buttons for power steps needed in testing were added. Arrow buttons for fine-tuning the power value and an OK button for executing the power set-up were added.
5	Unequal information (alarms, normal info) shouldn't be presented within the same frame.	Observability, failure management	Information within the alarm frame was divided into three separate frames based on the nature of the information. Normal information and alarms were separated.
6	Indicating that the diesel generator is running should be made easy.	Observability	Status text was not added. Instead, an indicator for diesel generator running was added to the ready-for-starting frame.
7	Same information shouldn't be presented in multiple places within one display.	Workload	The measurements frame was removed. Non-duplicate measurements were added into suitable frames.
8	Indication for if the diesel generator is ready for starting or not should be the first thing for the operator to see and clearly visible.	Observability, workload	The ready-for-starting frame was moved to the upper left corner of the display.
9	Information related to synchronizing should be combined within one frame.	Observability, workload	Synchronizing information and the control buttons were combined into one frame.
10	Buttons for starting and stopping the diesel should be clearly visible.	Observability, workload	The frame including the start and stop buttons was moved closer to the diesel frame and the other control buttons.
11	Power should be represented graphically instead of just a numerical value.	Observability	Power trend was added.

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ID	Change request	Related guidelines	Realized design
12	Timer to indicate for how long the diesel generator has been running without load should be presented.	Observability	Ignored due to limitations of ProcSee. Information is not available in the Fortum reference displays either.
13	Currents should be named 1, 2 and 3 instead of R, S, T.	Observability	Currents were named 1, 2, 3. According to the Fortum reference displays should be named U, V, W.
14	"Käynnistys varalle" (Standby start-up) should be named "Tyhjäkäynti" (No-load operation).	Observability	Text "(tyhjäkäynti)" was added.

Subsystem display

The subsystem display includes control buttons for and measurements from the subsystems of the emergency diesel system. These include prelubrication pump and lube oil, fuel forward pump to day tank and fuel, starting air compressor and starting air, jacket water preheating pump and jacket water, sea water pump and sea water, as well as secondary cooling water and turbo charger. Exhaust gas temperatures, coil temperatures and crankcase pressure are also displayed. Measurements of the key parameters of the diesel generator are displayed within their own frame, combined with navigation to the main display. Changes to the display layout and graphical representations were made based on the user evaluation. The change requests and realized design changes related to subsystem display are presented in Table 3. The final version of the subsystem display in a situation where everything is OK is presented in Figure 19. A situation where the temperature difference between the cylinders 1-8 is too high is presented in Figure 20. The alarm is indicated by red colour in the graphical representation of the temperatures and next to the numerical measurement frame. A blinking red frame around the display name indicates that there is something wrong on the display.

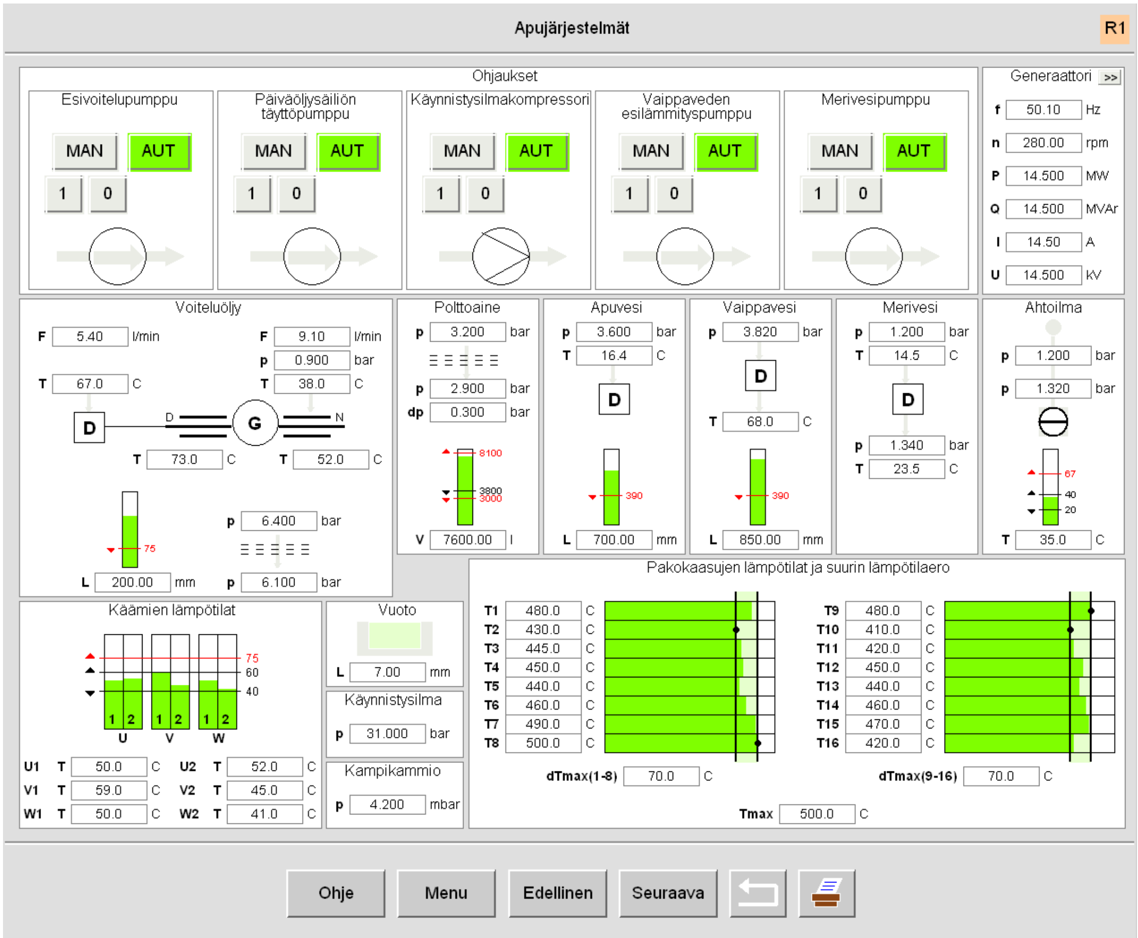

Figure 19: The final version of the subsystem display, case A (everything OK).

Table 3: Realized design changes for subsystem display.

ID	Change request	Related guidelines	Realized design
15	Current air pressure should be presented. Starting and stopping pressure don't need to be presented as such.	Observability	Starting and stopping air pressures were removed. Current start air pressure was added.
16	Level of second cooling water container (Apujäähdytysvesisäiliön pinnankorkeus) should be presented together with second cooling water (Apuvesi) instead of sea water (Merivesi).	Observability, workload	Level bar was added into the second cooling water frame and measurement was removed from the sea water frame.

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ID	Change request	Related guidelines	Realized design
17	Components should be named unambiguously (e.g. "Täyttöpumppu" ->"Päiväöljysäiliön täyttöpumppu").	Observability	"Täyttöpumppu" frame was renamed "Päiväöljysäiliön täyttöpumppu".
18	It should be clearly displayed between which cylinders the biggest temperature difference is. Frame header should indicate that temperature difference is presented in the frame instead of just temperatures of individual cylinders.	Observability	Frame header was changed. Black dots were added to indicate the cylinders with the lowest and highest temperatures.
19	Temperature difference of the coils should be presented.	Observability	Not added as no information on the limits was available. Temperature difference can be estimated from the bars and calculated from the numerical values.
20	The meaning of "Vuoto" (leakage) should be better explained.	Observability	Two different leakages are indicated with the same graphical representation. Should be checked when combined with the Apros model.
21	Normal and alarm limits should be presented more clearly (e.g. coil temperature).	Observability	Arrows to indicate top and bottom limit were added.
22	Information should be better organized. Controls should be together and measurements together.	Observability, workload	Controls combined within their own frame. Measurements organized logically as close to their related controls as possible.
23	Each subsystem could have their own displays, common display could be on a more general level.	Workload	No separate displays for each subsystem were made. Indication of display statuses was added to menu display.
24	The meaning of "Meriveden paine pulpetissa" is not clear.	Observability	Removed as is not represented in the Fortum reference displays either.

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ID	Change request	Related guidelines	Realized design
25	Temperature difference between cylinder groups should be presented.	Observability	Can be calculated from the numerical values if needed.

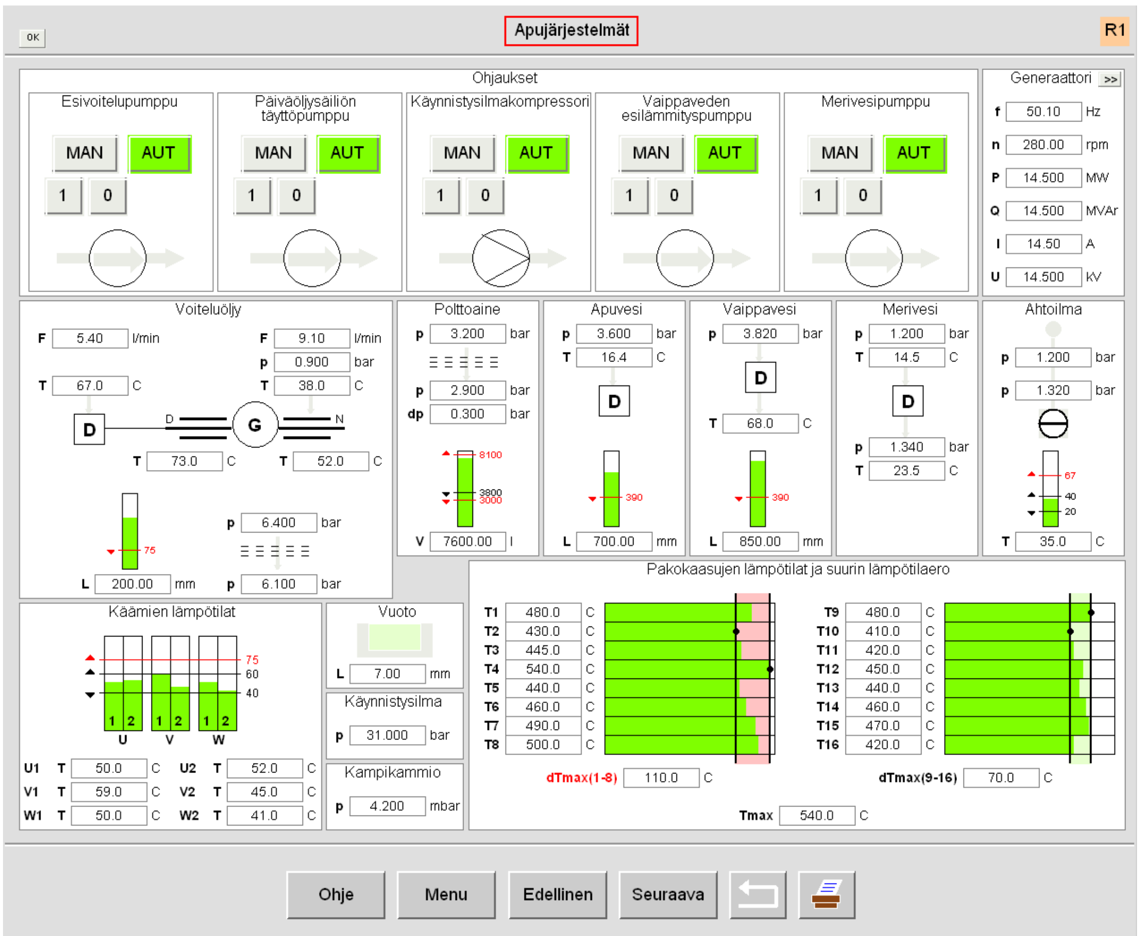

Figure 20: The final version of the subsystem display, case B (alarm).

Air-conditioning display

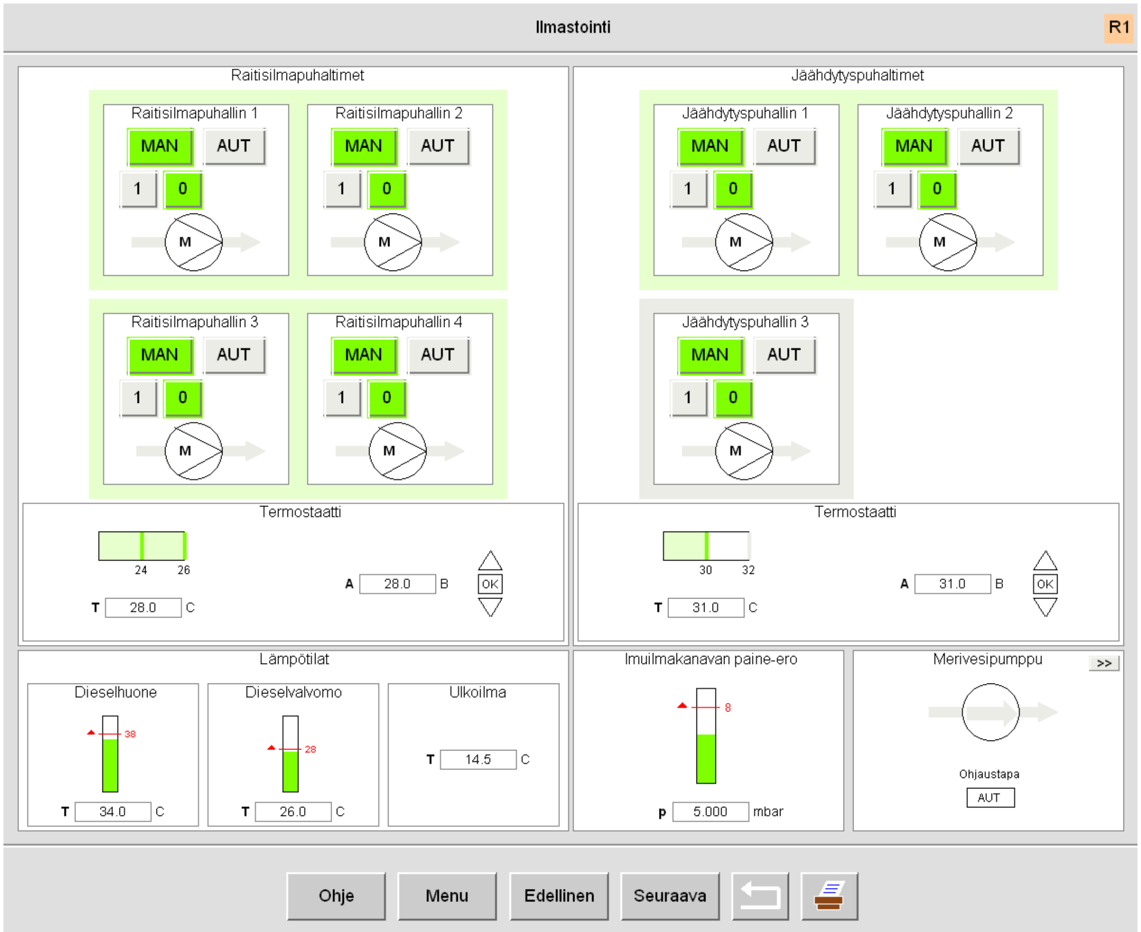

Figure 21: The final version of the air-conditioning display.

The air-conditioning display presents the fresh air fans and the cooling fans that control the temperature of the diesel room and the diesel control room. The fans are grouped with a related thermostat frame which includes a temperature display and a setter for the thermostat target temperature. The fans are surrounded by a colour-coded frame that indicates if the fans should be running (green) or not (grey). The frame colours are linked to the temperature steps in the graphical representation of the corresponding thermostat temperature. Also diesel room, diesel control room and outside temperatures, as well as the pressure difference in the air filter and the sea water pump status are displayed. Changes to the display layout and graphical representations were made based on the user evaluation. The change requests and realized design changes related to air-conditioning display are presented in Table 4. The final version of the air-conditioning display is presented in Figure 21.

Table 4: Realized design changes for air-conditioning display.

ID	Change request	Related guidelines	Realized design
26	Set point of thermostats should be visible.	Observability	Same kind of setters as for power were added (see change request 4 in Table 2).
27	It should be clearly indicated if a fan is running under manual control instead of automatic control.	Observability, failure management	Letter M was added to the fan symbols to indicate manual control (applicable also for pump and compressor symbols on the main display and the subsystem display).
28	Fans and thermostats related to each other should be presented within the same frame.	Observability, workload	Frames were added around the fan groups and their thermostats as well as around the temperatures.
29	Starting temperatures of the fans could be visible.	Observability	Coloured frames were added around the fans to indicate if they should be running or not.
30	Sea water pump should be presented on air-conditioning display.	Workload	Sea water pump was added on the display.

Ready-for-starting display

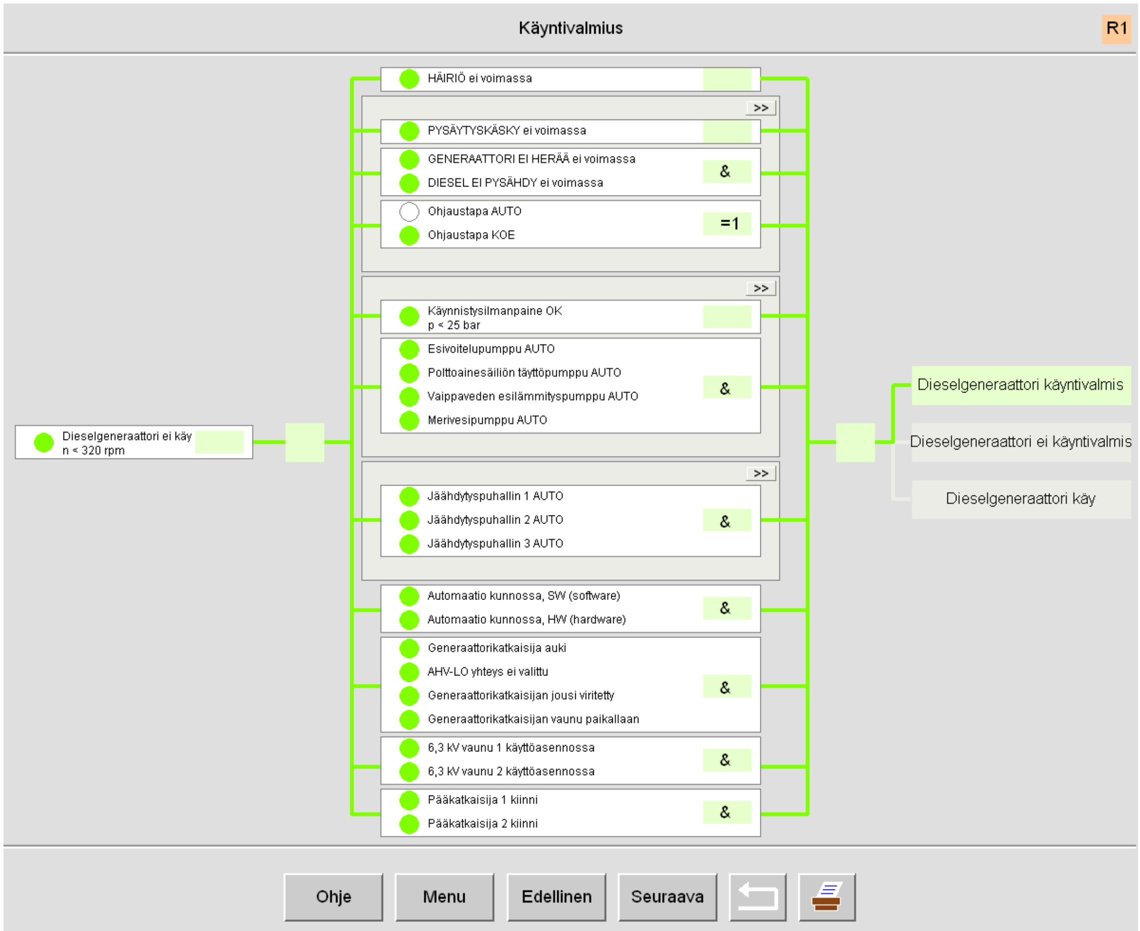

Figure 22: The final version of the ready-for-starting display, case A (ready for starting).

The ready-for-starting display presents the diesel generator status (ready for starting, not ready for starting or running) and the conditions leading to that status. The diesel generator is ready for starting if it isn't already running and if the statements in the middle of the display are true. The statements related to each other are combined within one frame and a logical operator is used for indicating the required combination of the statements. A green lamp on the left is used for indicating that the statement next to it is true, and the box on the right indicates the status of the whole frame. In case there is a malfunction somewhere, indicated by a red box and a red line leading to the corresponding statement frame, the generator is not ready for starting. It is possible to navigate to the corresponding display to find out more about the malfunction. Minor changes to the display layout and graphical representations were made based on the user evaluation. The change requests and realized design changes related to ready-for-starting display are presented in Table 5. The final version of the ready-for-starting display in a situation where the diesel

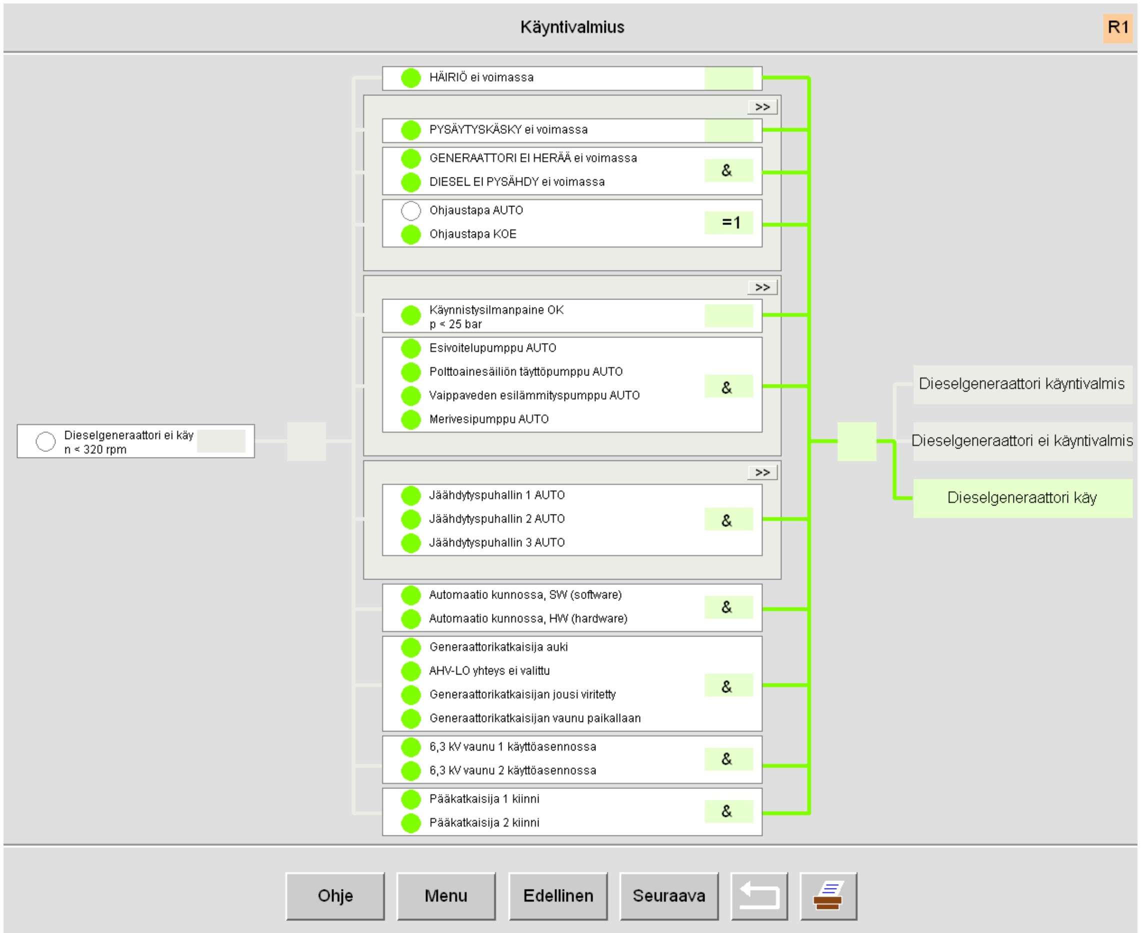

Figure 23: The final version of the ready-for-starting display, case B (running).

generator is ready for starting is presented in Figure 22. The situation where the diesel generator is already running is presented in Figure 23 and a situation where it is not ready for starting due to a malfunction in Figure 24.

Table 5: Realized design changes for all logic displays.

ID	Change request	Related guidelines	Realized design
31	The situation where the diesel generator is already running (n >320 rpm) should be clearly indicated (Ready-for-starting display).	Observability	A third option “Dieselgeneraattori käy” (Diesel generator running) was added to the right.

Continued on next page...

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ID	Change request	Related guidelines	Realized design
32	Symbols for logical operators should be used instead of text AND (JA)/OR (TAI).	Observability	Text was changed to logical operators.
33	Grey lamps shouldn't be used.	Observability	A white circle with a grey outline was used to indicate a lamp that is not on instead of a grey circle.
34	Plus sign shouldn't be used in the connection square.	Observability	Plus sign was removed.

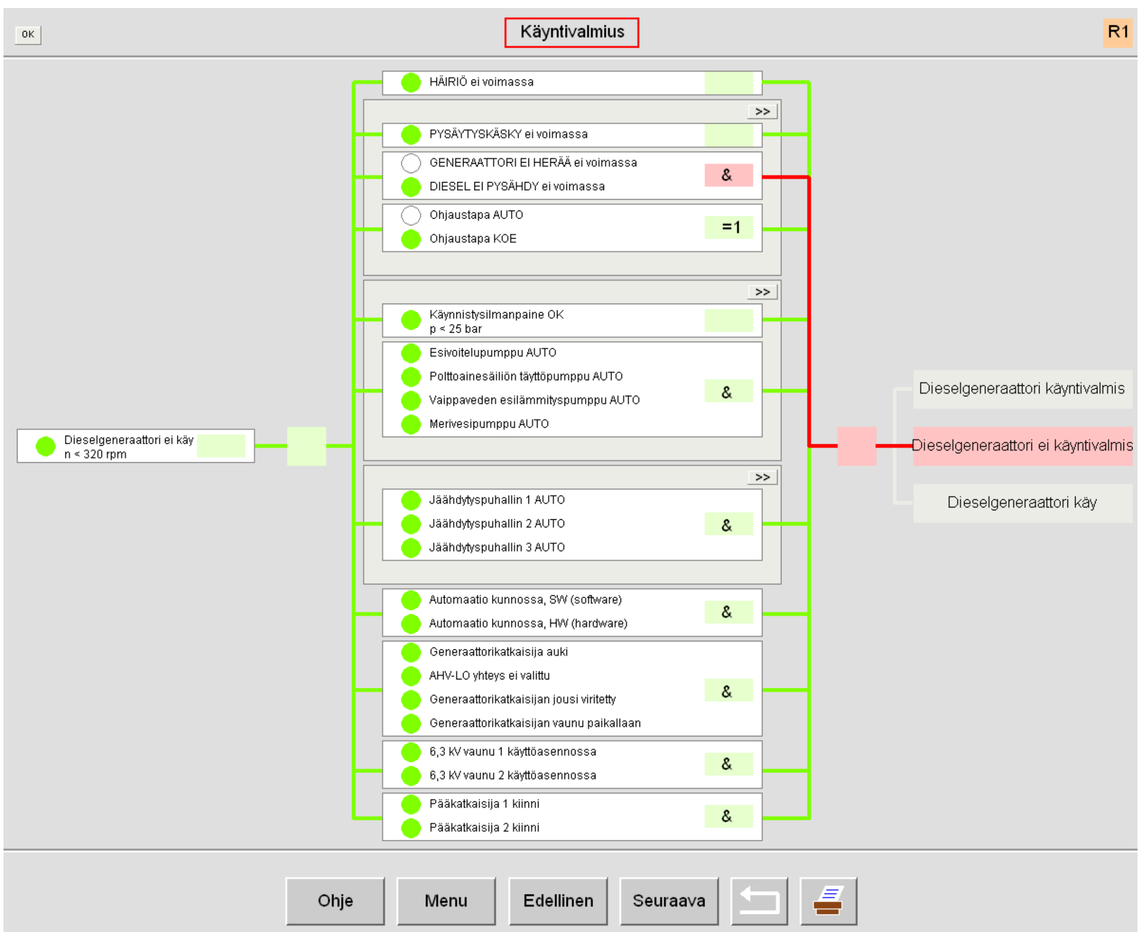


Figure 24: The final version of the ready-for-starting display, case C (not ready for starting).

Fault display

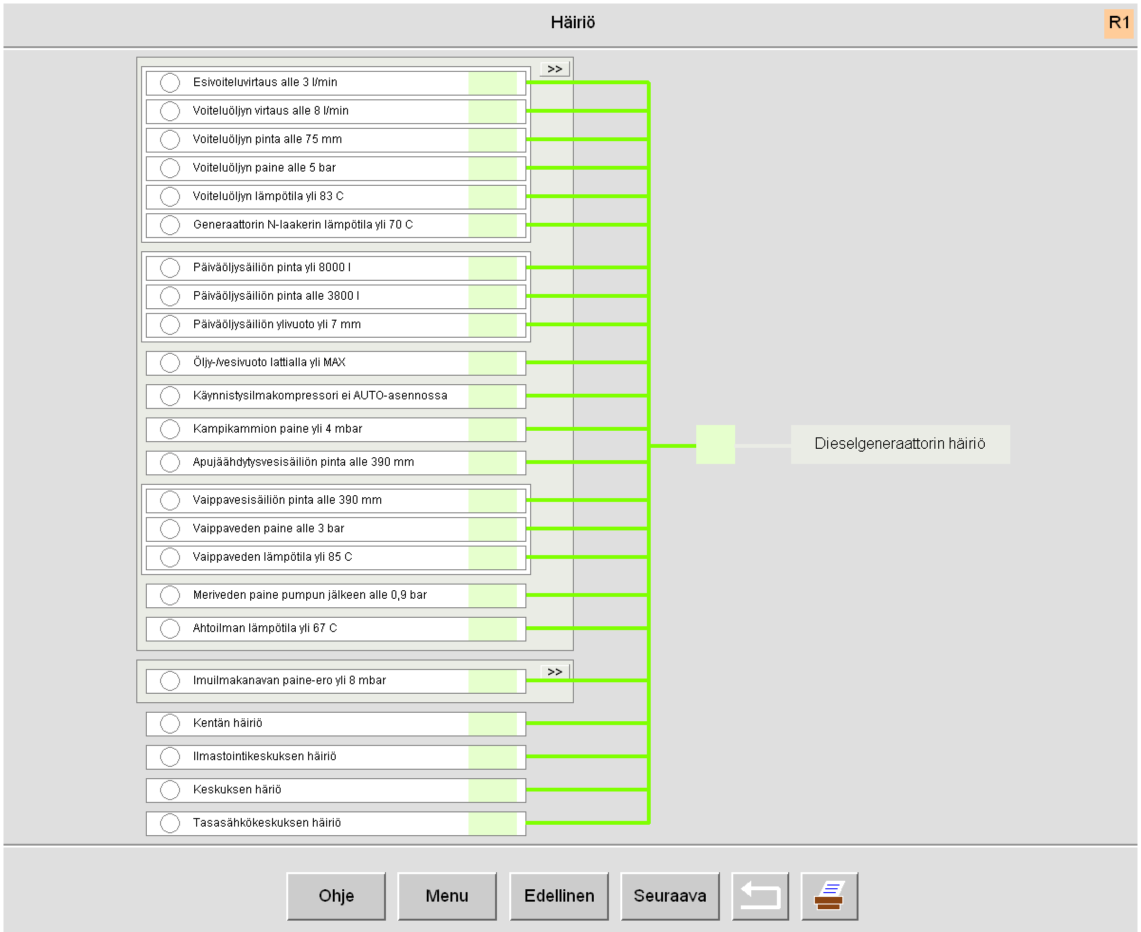


Figure 25: The final version of the fault display, case A (no fault).

The fault display presents the conditions leading to diesel generator fault. The diesel generator fault status is presented on the right and the statements leading to diesel generator fault on the left. Each statement is presented within their own frame, the state of which is indicated by both the lamp on the left and the green/red rectangle on the right. The statements related to the same subsystem are surrounded by a combining frame. It is possible to navigate from the fault display to the subsystem display and to the air-conditioning display if more information on the situation is needed. The change requests and realized design changes related to fault display are presented in Table 5 (change requests 32-34). The final version of the fault display in a situation where there are no malfunctions is presented in Figure 25. An example of a situation where there is a fault is presented in Figure 26.

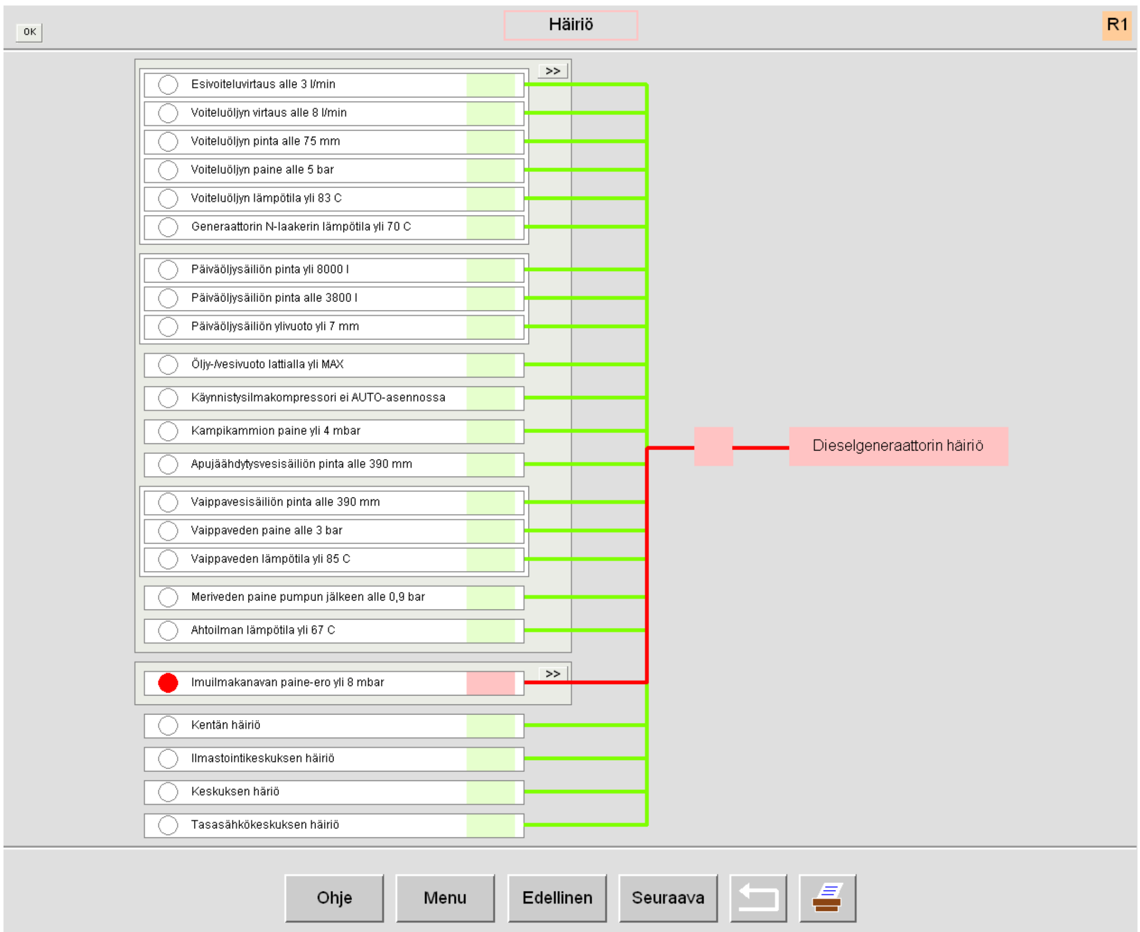


Figure 26: The final version of the fault display, case B (fault).

Trip display

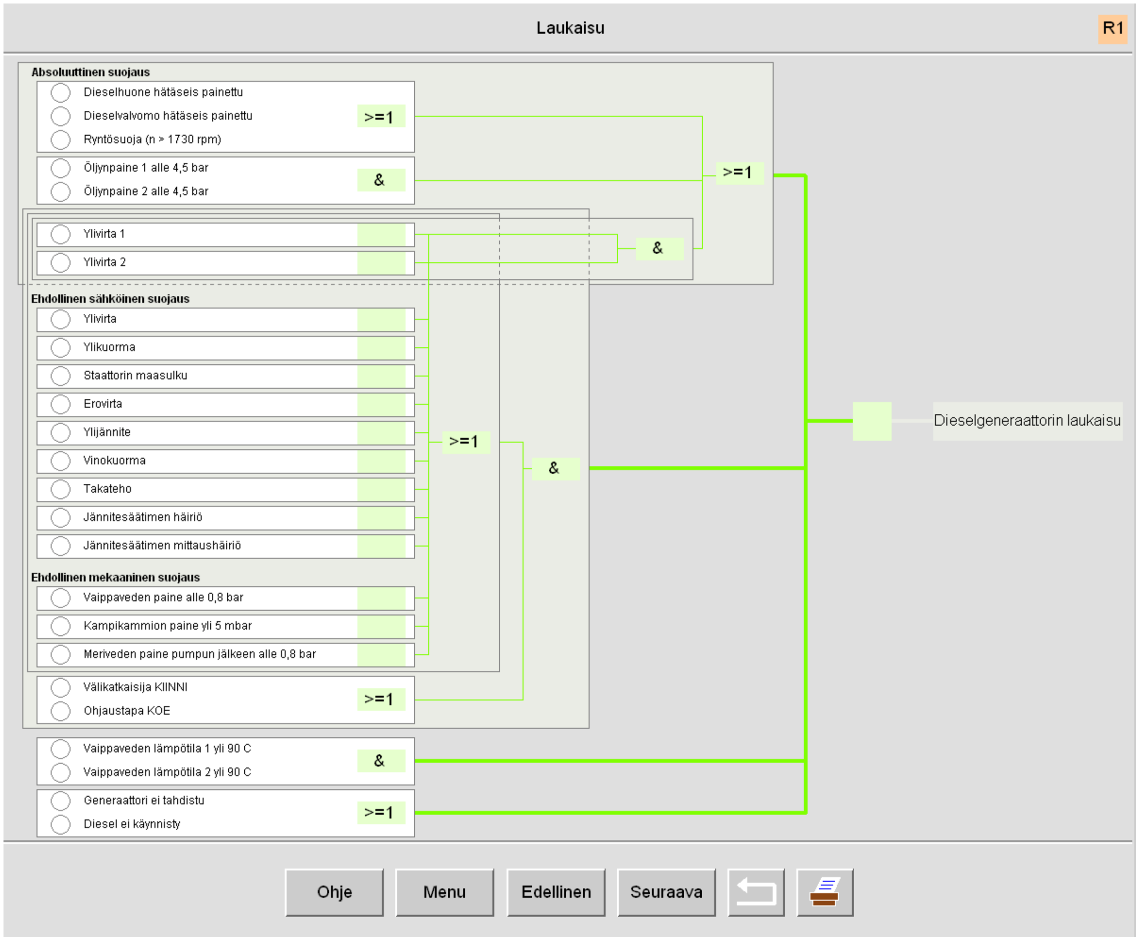


Figure 27: The final version of the trip display, case A (diesel generator trip not triggered).

The trip display presents the conditions leading to diesel generator trip. The diesel generator trip status is presented on the right and the statements leading to the trip on the left. As the triggering conditions for the diesel generator trip are fairly complicated and some statements are taking part in multiple trigger conditions, there are some overlapping frames on the display. It is, however, easy to locate the source of the trip by following the lines leading from the statements to the diesel generator status indicator. The final version of the trip display in a situation where there are no malfunctions is presented in Figure 27. A situation where there is a malfunction leading to diesel generator trip is presented in Figure 28.

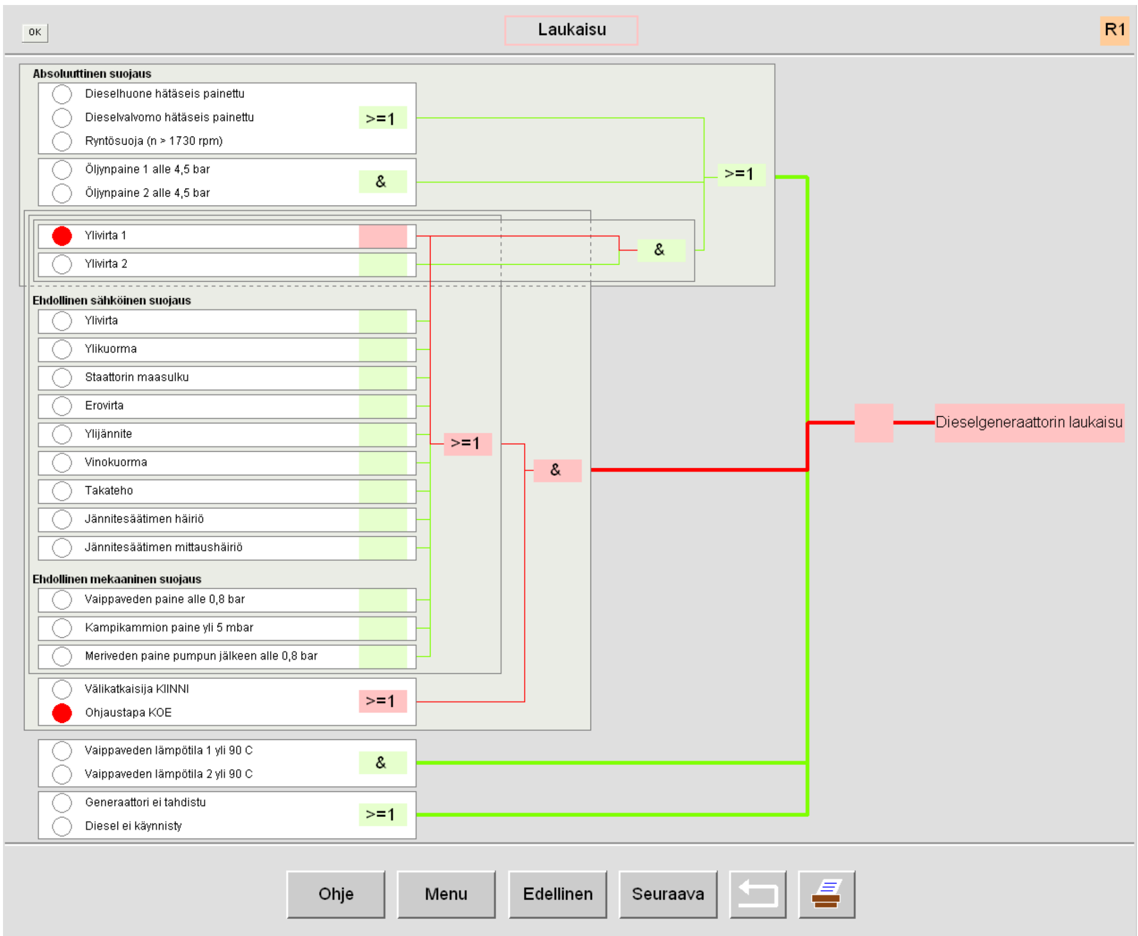


Figure 28: The final version of the trip display, case B (diesel generator trip triggered).

6 Results

This sections goes through the results of the research. The research problem was to find a way of presenting automation information so that the operators gain sufficient level of automation awareness without facing the problem of information overload. This problem was addressed both by reviewing literature on automation awareness and the factors affecting it, as well as designing and developing a user interface for a simulator environment with the help of guidelines derived from literature. The following three research questions arose from the research problem:

1. How can automation awareness be defined and what is sufficient automation awareness based on literature?
2. Which (user interface related) factors affect the operators' automation awareness?
3. How can user interface solutions support automation awareness and competence?

These questions are answered in the subsections of this section. Section 6.1 goes through the first two questions based on the theory presented in sections 2 and 3. Section 6.2 answers the third question by reviewing the theory in Section 4 and going through the developed user interface focusing especially on observability, workload and failure management - the key factors leading to a good automation user interface design defined in Section 4.2.

6.1 Automation awareness

The concept of automation awareness was approached from different angles. As the term is originally invented in the SAFIR programme, this thesis relies strongly on the assumptions made within the programme. However, the purpose of the thesis was to expand the definition of automation awareness and explore it more thoroughly than done so far. This was done by reviewing literature from various fields involving humans working with automation. As automation awareness is rarely referred to in literature as such, the definitions in this thesis are derived from studies e.g. on situation awareness and on human-automation collaboration.

How can automation awareness be defined and what is sufficient automation awareness?

Automation awareness can be seen as a part of situation awareness - the operator's understanding of the current situation - that gains more significance with the increasing automation. On the other hand, automation awareness can be viewed more widely as proper understanding of, trust in and cooperation with automation. It is widely recognized (e.g. [6, 17, 18]) that difficulties in understanding automation can lead to problems in cooperation between human operators and the automation. Due to automation reformation in the Finnish nuclear power plants, automation is both taking more control over the processes in the plant and getting more complex. This leads to a situation where it is both more important and more difficult for the operators to understand the automation in order to be able to operate the plant appropriately. Being aware of the automated functions and properties of the automation is crucial for the operators, as with automation becoming more powerful, the role of people actually becomes more important [18]. The flexibility and adaptivity of humans, along with their anticipation abilities, are valuable assets that should be utilized in joint human-automation systems. However, it is impossible for the human operators to react quickly and take appropriate actions in case of an automation malfunction if they haven't been able to follow the actions of the automation and understand how it works. Besides causing problems in working with the automation itself, lack of sufficient automation awareness may also interfere with the normal process operations by e.g. decreasing situation awareness [7, 17], affecting the operators' feelings towards the whole system [3, 7, 22] and adding to operator workload [7, 21].

This thesis defines the development and maintenance of automation awareness as *a continuous process that comprises of perceiving the current status of automation, comprehending the status and its meaning to the system behaviour as well as estimating the future statuses and their meanings*. These phases may happen simultaneously and partly unconsciously, in addition to consciously observing the automation, and will eventually lead to decisions and actions that affect the system state. This again has an effect on the automation, making the human operator a part of the whole system instead of an external observer, so constant updating of automation awareness is needed.

Various factors from individual abilities of the operator to automation properties affect the formation of automation awareness, so it is difficult to create a universal model for reaching optimal automation awareness in every situation. Also defining the accomplished level of automation awareness is hard, as the experienced awareness depends significantly on the operator's feelings towards the automated system and may differ from the measured theoretical awareness. Dividing automation awareness into hierarchical levels from information being available to information being subject to higher level cognitive processing, as done by Hourizi & Johnson [24], may help assessing both the operator's current level of awareness and the system's capability to support the development of automation awareness.

Sufficient automation awareness can be defined as the operator's *understanding* of the automation, along with their *skills to interact* with it and their *will to cooperate* with it, on such a level that leads to safe and efficient operation of the nuclear power plant in all situations. The challenge is to provide adequate automation awareness without overloading the operator. This can be accomplished through careful design of the automation, the user interfaces, the cooperation between human operators and automation, and of the whole system formed by the process, the automation and the human operators.

Keys to sufficient automation awareness seem to be maintaining the human operator active and engaged, making the automation observable by providing feedback of its actions, offering enough information on the automation's operating principles and distilling the data to appropriate level of oversight. Exact guidelines for what kind of information to present and how don't yet exist as defining them would require thorough research on the development and maintenance of automation awareness under different conditions.

Which factors affect the operators' automation awareness?

Automation awareness in a nuclear power plant control room is affected by multiple factors, often interrelated with each other. Key contributors to the development of the operator's automation awareness are the properties of the automation itself, the human-system interface and operator training.

Automation properties known to have an effect on automation awareness are the level of automation, automation complexity, modes, functions and processes of automation, as well as the flexibility and reliability of automation [2]. Level of automation affects the level of engagement of the operator, automation complexity has an effect on its intelligibility. Multiple modes add to automation complexity and decrease predictability. Functions and processes of automation affect the operating principles of the automated system. Flexible automation adapts its level to situation and may thus reduce the out-of-the-loop effects of highly automated systems, but on the other hand, changing level of automation may cause unpredictability. Reliability of automation affects calibration of trust and the operators' use of the system. Other properties of automation, such as correction and compensation functions [28] and unpredictable behaviour under unexpected situations [2], also have an effect on automation awareness.

Feedback from automatic activities is essential for maintaining awareness of the automation. Lack of feedback and poor communication of what the automation is doing and why decrease the observability of the automation and thus the operators' automation awareness [2], whereas appropriate feedback helps the operators in assessing the automation status during operation and thus increases the awareness.

The level of current *workload* can affect the development of the operators' automation awareness be it high or low. Decreased awareness may result from boredom and lack of attention under low workload or from insufficient capacity to maintain awareness under high workload [8].

Operator *training* is the base for understanding automation, the conditions under which it should or shouldn't be used, as well as its algorithms and different modes of operation [2].

The *human-system interface* is the boundary between the operators and the automated system. Poorly designed interface can reduce automation awareness by not displaying relevant information or by using information visualization methods that are easily misinterpreted [2, 6]. On the other hand, it is assumed that a good user interface can support the development and maintenance of automation awareness. The next Section discusses further how this can be achieved.

6.2 User interface

The focus of this thesis was on user interface solutions that support the development and maintenance of the operators' automation awareness in nuclear power plant control rooms. Thus, the principles for successful human-automation cooperation and automation interface design were reviewed. This information was then applied to practice by designing and developing a user interface for a simulator environment following the guidelines derived from literature analysis.

Human-automation cooperation exists at some level in any field where there are humans and automation working together. Successful cooperation leads to optimal performance of the joint human-automation system, whereas problems in cooperation may result in efficiency and safety issues. Several factors affect the success of human-automation cooperation and many suggestions for improving the cooperation have been made. Considering the user interface, special care should be put on supporting the interaction between human operators and automation [2], representing information about the automation to provide common ground [30], supporting failure management and calibration of trust [17] as well as minimizing workload required for dealing with the automation [2, 17].

As the human-system interface is the only boundary between the operators and the automated system, most of the cooperation happens through the HSI. In order to be able to interact with the system, the operators need to learn the structure and language of the interface [33]. These depend on the selected information visualization approach. To make the operator's work more manageable instead of complicating it, the visualization method should exploit cognitive strengths and reduce cognitive loading [34]. What comes to presenting automation-related information in the user interface, the keys to successful presentation seem to be good observability, minimized workload and transparent failure management. The following sections go through the user interface designed and developed within this thesis in terms of those three parameters.

6.2.1 Observability

Section 4.2.1 discusses design principles that lead to good observability of an automated system. The amount of observability depends on the feedback provided by the system as well as the information presentation methods used in the user interface. The user interface developed for the simulator environment follows the observability guidelines in that it

- gives insight into the process the automation is guiding by
  - representing the key process parameters graphically on the process displays
  - combining relevant information together, e.g. rotation speed and processes initiated during different phases of diesel generator start-up (see Figure 29)

  - presenting the diesel generator status and factors affecting it on the logic displays

- utilizes the human strengths by

  - providing information in a form that supports perceiving change and recognizing patterns, such as measurement bars and logic diagrams with changing colour (see Figure 30)

- uses self-descriptive information presentation means compatible with the operators' expectations, for example

  - logical operators
  - green and red colour
  - arrows to indicate the top and bottom limits for measurements

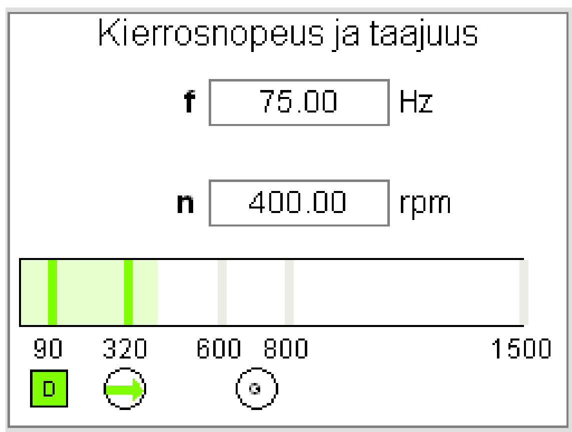
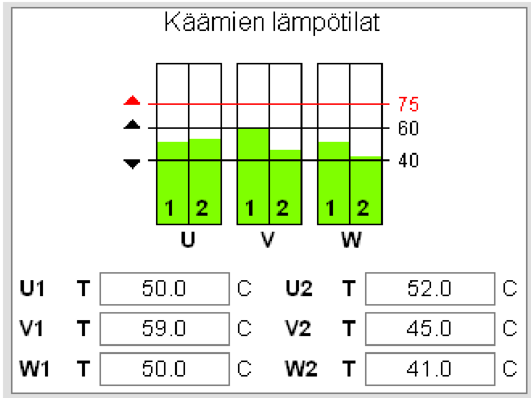
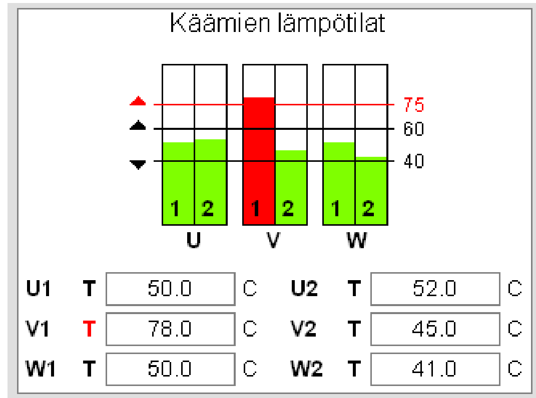


Figure 29: Graphical representation of rotation speed and the processes initiated during the diesel generator start-up.

Section 4.2.1 lists several types of information that ensure good observability of the system. As not much was known of the automation guiding the emergency diesel system, no information on the automation itself, such as the algorithms used by the automation or data sources, is presented in the user interface as such. However, the logic displays can be used to discover why the system has arrived to its current state. Information such as the synchronizing meters and the rotation speed diagram enables both anticipating what the automation will do next and determining that it is functioning correctly. Instead of adding several new automation displays, the design aimed for clear presentation of process information with key automated functions integrated into the process and logic displays.



(a) Graphical representation of coil temperatures that are within normal limits.



(b) Graphical representation of coil temperatures when V1 temperature is over the alarm limit.

Figure 30: The measurements are displayed with bars that change their height and colour based on the measured value.

6.2.2 Workload

Minimizing the workload needed for managing the user interface is essential for optimal performance. Section 4.2.2 goes through factors that affect the workload and suggestions on how to decrease it. Secondary tasks like looking for a suitable display, looking for relevant information on that display and trying to understand the meaning of the information all add to operator workload. The simulator user interface minimizes the effort needed to these tasks by following the guidelines presented in Section 4.2.2.

The workload associated with searching for a display is decreased by using only the three process displays and three logic displays and integrating the information related to automation into these displays. Unnecessary browsing of displays is avoided by providing key information from other displays where it is needed. Hierarchical presentation of information is implemented in the form of a menu display that gives an overview on all displays and the overall status of the system. Multiple ways to navigate between the displays are provided in order to minimize the steps needed for changing the display. Each display can be reached from any other display with a maximum of two mouse clicks.

To minimize the workload needed for finding the correct information on a display and understanding its meaning, the measurements and other user interface components related to each other are grouped into frames with a clarifying header. Information is organized into meaningful patterns, such as the logic diagrams and the groups of different fans on the air-conditioning display.

Automatic updating of displays, such as opening the fault display when there is a fault, or filtering data based on the current situation suggested by some literature sources ([11, 27]) are not implemented as they might distract the operators from what they are currently doing and cause important information to be missed.

6.2.3 Failure management

The third important thing to consider when designing an automation user interface is how the process and automation malfunctions are managed. Section 4.2.3 discusses the principles of transparent failure management. As the background information about possible automation failures was limited to what is displayed on the qualified display system draft displays and was transferred to the developed displays as such, this section concentrates on managing process failures through the user interface.

As many of the malfunctions lead to a change in diesel generator status, they can be followed on the logic displays. The ready-for-starting display includes statements related to automation status (software and hardware), along with the operational status of some pumps and fans and states of hardware such as the generator switch. Some of the malfunctions can be examined further by navigating to the related display. The fault display presents some process alarms, as well as malfunctions related to e.g. electricity transmission, leading to diesel generator fault. The trip display includes trigger conditions related to absolute shielding as well as conditional electric and mechanic shielding of the nuclear power plant.

Specific alarm displays weren't designed within the thesis but each process display presents the alarms related to the components on that display. Whenever there is an abnormal situation on any display, it is indicated by a blinking red frame around the display name. As continuous blinking can distract the operator rather than help them, the alarms can be acknowledged by clicking an OK button. This causes the blinking to stop and displays a stationary red frame instead. The individual alarms within a display are always stationary.

All the display statuses are displayed on the menu display, through which it is easy to navigate to any display with an abnormal status.

6.3 Summary of results

The development and maintenance of automation awareness was defined as a continuous process affected by multiple factors. The focus of the thesis was on user interface solutions that support the automation awareness, so the research concentrated on user interface related factors. Three key guidelines for successful automation user interface design were defined:

- Provide good observability of the automation
- Minimize the workload required for working with the automation
- Offer transparent failure management for both process and automation failures

Figure 31 summarizes the guidelines leading to a successful automation user interface design and thus increasing the operators' automation awareness.

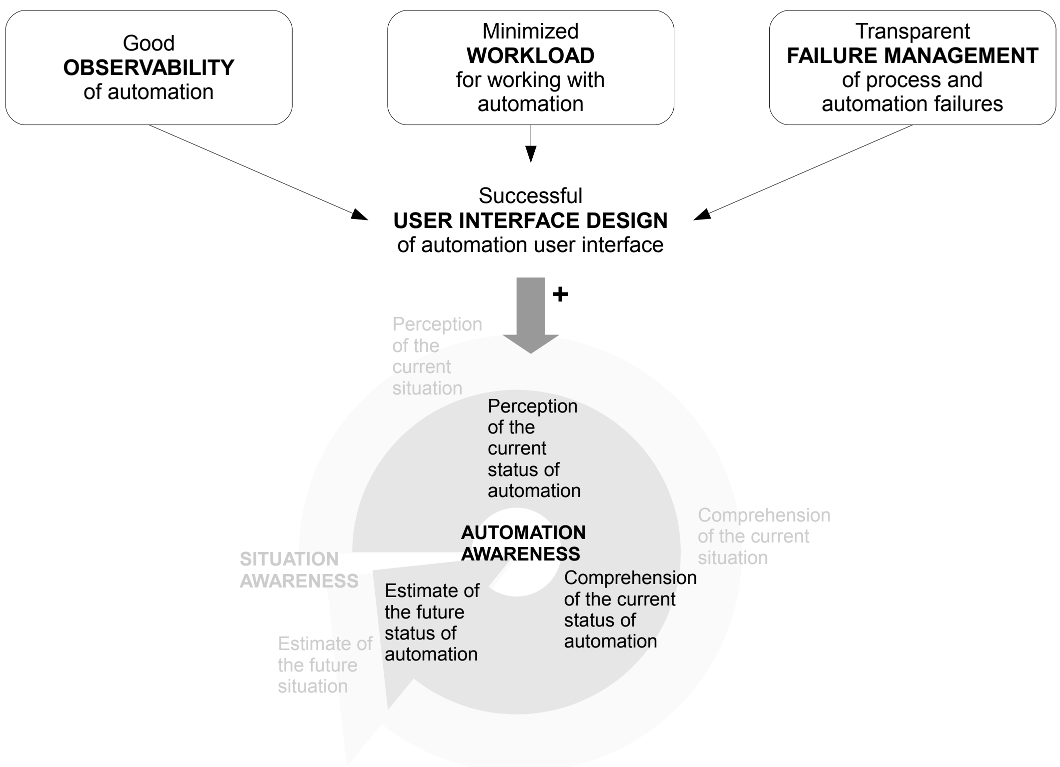


Figure 31: The three guidelines for successful automation user interface design.

7 Discussion and conclusions

This section summarizes the work done within this thesis, discusses the credibility and validity of the research and gives ideas for future research in the field of automation awareness. In Section 7.1 a summary of the research, along with the drawn conclusions, is presented. Section 7.2 discusses the credibility and validity of the research and Section 7.3 goes through the future research plans and suggestions.

7.1 Summary and conclusions

Along with control room digitalization and increase of automated systems comes a significant change on operator work. In order to ensure safe and efficient operation in future nuclear power plants, the effects of new technologies need to be thoroughly investigated. Special care is needed as large-scale automation reformations haven't been made before and little knowledge of possible risks is at hand. Increasing level of human factors research is required for creating sustainable control room designs as digital control room solutions put even more weight on the human operators' role than did the conventional ones.

This thesis addressed the subject by reviewing literature on human-system interface design, situation awareness, human-automation cooperation, and human factors in nuclear industry and automation design. Based on the literature, it is clear that digitalization and increased automation have an effect on the operators' work environment and tools, the ways of working and the organization as well as the individual operators. Changes affect the overall performance of the joint system formed by the human operators and the digital I&C systems of the plant. Due to automation's key role in the changes, potential issues resulting from them can be largely avoided by increasing the operators' understanding of automation, skills to interact with it and will to cooperate with it. This leads to introducing the concept of automation awareness. Despite of not being referred to in literature as such, the need for adequate automation awareness has been widely recognized. It is no longer enough for the operators to understand the process and its states but they also need to follow the progress of automated functions in order to operate the plant properly. Thus, automation awareness can be seen as a significant part of situation awareness.

In this thesis the concept of automation awareness was introduced, and automation awareness was discussed alongside with situation awareness. The level of automation awareness that is sufficient for operating a nuclear power plant was discussed, and the difficulties of determining if the operators' automation awareness is on an adequate level were addressed briefly. The various factors affecting the development and maintenance of the nuclear power plant operators' automation awareness were listed.

The practical goal of this thesis was to design and develop a user interface for a simulator environment that is to be used for automation awareness related studies. The design process aimed for finding methods for presenting automation in the user interface in a way that supports automation awareness. In order to reach this goal, guidelines for human-automation cooperation and for designing automation HSIs were gathered from literature. Three key contributors to successful automation user interface design were found: observability of the automation, required workload for working with the automation and failure management of both process and automation failures. Background material from Fortum was used for determining the contents and structure of the user interface and a user evaluation with control room operators was done to improve the initial design. The final design was implemented with the user interface management system ProcSee.

7.2 Credibility and validity of the research

The terms credibility and validity are used here to describe the trustworthiness and thus the overall quality and value of the research.

Based on the literature analysis done within this thesis, it is clear that the concept of automation awareness is valid and research on the subject is justified. As no ready-made definitions of the essence of automation awareness are yet available, the researcher is given the freedom of defining the term according to their own insight. This thesis discusses automation awareness in nuclear power plants and covers therefore just a small subset of the whole issue. As more and more functions in our everyday life are being automatized, the significance of automation awareness grows substantially on all fields. Automation awareness should be taken into account in design and its development and maintenance should be supported. A full and unambiguous definition of the term would, however, require thorough research on many fields over a long period of time and the discussion in this thesis should be viewed only as a preliminary introduction to the subject.

In this research, literature from various fields, such as military operations and aviation in addition to nuclear industry, was reviewed in order to understand the concept of automation awareness in nuclear power plant control rooms. As the relationship between humans and automation, as well as the characteristics of the automation, the work environment and the organization vary between the different fields, the information gathered from other fields may not be directly applicable to nuclear power plant control rooms. It is, however, assumed that the general principles of human-automation cooperation and the effects of automation on human work are somewhat universal and can be used as a baseline in automation awareness related research.

The practical part of this thesis presents a user interface solution that is assumed to support the development and maintenance of the nuclear power plant control room operators' automation awareness in the context of the emergency diesel power generation system. The design is based on background material offered by Fortum and the theoretical design principles defined in Section 4. The background material was fairly limited and incoherent, consisting of user guides related to the old emergency diesel system along with incomplete display drafts of the new system. This combined with fairly limited previous expertise on nuclear power plants caused uncertainty during the initial design of the user interface. There was, however, enough background material for making an educated guess of the possible user interface that was then evaluated with the users.

User evaluation was used for determining whether the initial design of the user interface is suitable for operating the system and how it could be improved. The evaluation was done with a group of eight control room operators from Loviisa nuclear power plant as a part of training on automation competence in digital control rooms organized by VTT. Evaluation data was gathered through discussions lead by VTT representatives. Useful information was obtained from the discussions but some factors that restrict the credibility of the user evaluation do exist. First of all, the group of operators participating in the evaluation was fairly small and the individual operators weren't selected specifically for the research. However, the evaluation group's capability to assess the quality of the display design was good, as the group consisted of operators with various backgrounds and expertise. Secondly, two of the three VTT representatives leading the discussions weren't familiar with the design to be evaluated and had only a quick briefing on the displays before the discussions. Both of the mentioned representatives have, however, strong expertise in human factors and usability research, as well as in research on automation awareness, so their abilities to lead the discussions were sufficient. Thirdly, the time for the discussions was very limited. More user findings could have been brought up had there been more time, but all the groups managed to cover all the displays under evaluation within the given time.

The final design and development of the user interface was done based on the results of the user evaluation. Minor details outside the user findings were also added. Due to the limited scope of the thesis, the final design wasn't evaluated with the users. As most change requests were unambiguous, it is assumed that the final design meets the demands expressed by the users during the initial user evaluation.

7.3 Future work

This thesis introduced the concept of automation awareness and discussed it regarding control room operators in nuclear power plant control rooms. In addition to that, guidelines for presenting automation in control room user interfaces were given. Based on the theory, a user interface for a simulator environment was designed and developed.

This thesis gives a general idea of the concept of automation awareness and shows its significance in the design of future control rooms. More thorough research is needed to define the term extensively and unambiguously. The definition of what is sufficient automation awareness for the nuclear power plant operators and how can an adequate level of automation awareness be reached remains still open. Some suggestions of what needs to be known about the automation controlling a process and how to present the information have been gathered, but further research is needed for proper guidelines on the subject.

The question of how the level of automation awareness can be measured is hoped to be answered with the help of the simulator environment studies in the future. For this to succeed, the user interface designed and developed within this thesis needs to be combined with the Apros model of the emergency diesel power generation system and test scenarios for studying the automation awareness, along with measurement tools, need to be developed. After finishing the development of the simulator environment, it can be used as an effective and versatile tool in many kinds of automation awareness related studies aiming for more thorough understanding of the concept.

Questions of the long-term implications of digitalization and increased nuclear power plant automation remain and more research is definitely needed in the field of automation awareness. The research can also be expanded on other fields from aviation and military operations to everyday automation awareness related to e.g. cooperation with home automation. Undoubtedly, the literature review has proved that the need for understanding automation more thoroughly is real and this understanding should be supported by the designers of automated systems and user interfaces.

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A User evaluation questions in Finnish

1. Kysymyksiä näytöistä - yleistä
   (a) Onko näytöillä esitetty kaikki hätädieselin koestuksessa/käytössä tarvittava tieto (poislukien trendit ja hälytykset)?
   (b) Onko tieto jaettu järkevästi eri näytöille?
   (c) Onko tieto ryhmitelty näytöillä selkeästi?
   (d) Onko näytöillä esitetty turhaa tietoa?
   (e) Onko näytöissä käytetty esitystapoja, joita et ymmärrä?
2. Kysymyksiä näytöistä - päänäyttö
   (a) Kierrosnopeus: auttaako kierrosnopeuden porrasmainen esitystapa hahmottamaan dieselin käynnistymisen vaiheet (90 rpm - moottori käynnistyy, 320 rpm - merivesipumppu käynnistyy, 600-800 rpm - generaattori herää, 1500 rpm - diesel tyhjäkäynnillä)?
   (b) Tehon ja loistehon asettelu: onko liukukytkin sopiva välinen tehon asetteluun? Onko asettelu lukuarvon antamalla tarpeellista?
   (c) Tahdistusmittarit: onko esitystapa selkeä? Onko tahdistustietojen esittämisestä hyötyä automaattisen tahdistuksen aikana?
   (d) Virta: onko eri virtojen vertailu toisiinsa tarpeellista?
   (e) Olisiko hyödyllistä esittää muita mittauksia kuvan avulla, mitä?
   (f) Mikä ohjaustapa on valittuna?
   (g) Mikä on pyörimisnopeus tällä hetkellä ja mitä se tarkoittaa dieselin käymisen suhteen?
   (h) Onko voimassa hälytyksiä?
3. Kysymyksiä näytöistä - apujärjestelmät
   (a) Pakokaasujen lämpötilaero: onko esitystapa selkeä?
   (b) Käämien lämpötilat: onko lämpötilojen vertailu tarpeen?
   (c) Mittausten ja komponenttien asettelu: ovatko irralliset kokonaisuudet (pumput ohjausten yhteydessä, mittaukset "palasteltu") ymmärrettäviä vai tulisiko vastata enemmän todellisuutta?
   (d) Mikä on sylinterien 8-1 pakokaasujen suurin lämpötilaero?
   (e) Mitkä pumput ovat käynnissä? Mikä on niiden ohjaustapa?
   (f) Mikä on voiteluöljyn lämpötila ennen moottoria? Entä ennen N-laakeria?
   (g) Onko voimassa hälytyksiä?
4. Kysymyksiä näytöistä - ilmastointi

(a) Minkä puhaltimien pitäisi olla päällä termostaattien lämpötilan perusteella (30 C - jäähdytyspuhaltimet 1 ja 2, 32 C - jäähdytyspuhallin 3 — 24 C - raitisilmapuhaltimet 1 ja 2, 26 C raitisilmapuhaltimet 3 ja 4)? Ovatko ne? (Miksi eivät?)

(b) Onko dieselvalvomon lämpötila korkeampi vai matalampi kuin ulkoilman?

5. Kysymyksiä näytöistä - käyntivalmius

   (a) Esimerkkikuvista A-D: Onko diesel käyntivalmis? (Miksi ei?)

   (b) Miltä näyttäisi jos ohjaustapa ei olisi AUTO eikä KOE?

6. Kysymyksiä näytöistä - häiriö

   (a) Esimerkkikuvista A-D: Onko häiriö voimassa? (Miksi?)

B Change requests and design suggestions

The original user findings in Finnish, as well as the change requests and their priority classes and related design guidelines, along with the design suggestions are presented in Table 6 starting from the next page.

Table 6: Change requests gathered based on user evaluation.

ID	User finding	Change request	Priority	Related guidelines	Design suggestion
		General findings			
1	Tietojen asettelu oikeaan järjestykseen, vasemmalta oikealle ja ylhäältä alas.	Information should be presented in logical order (from left to right and from top to bottom).	2	Observability, workload	Some information can be reorganized.
2	Näyttöjen otsikot isommalla fontilla.	Display headers should be written in a bigger font size.	5	Observability	Font size in final application will be selected to be big enough.
		Main display			
3	Kierrosnopeus turha esittää porrasmaisesti, ei ehdi kuitenkaan seurata. Jotain järkeä voisi olla jos seurattavat asiat olisivat samassa yhteydessä.	Rotation speed shouldn't be represented with a step-like diagram. Rotation speed reaches its highest value (1500 rpm) in seconds and stays constant after that. If processes that are initiated during each speed step are to be followed they need to be represented next to the diagram.	2	Observability	Rotation speed could be represented in the same manner as the thermostat temperatures on air-conditioning display or as a numerical value. Small symbols indicating the initiated processes could be put next to rotation speed diagram.

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ID	User finding	Change request	Priority	Related guidelines	Design suggestion
4	Teho ja loisteho: liukukytkin ei välttämättä hyvä. Pitäisi olla asteikko kilowatteja eikä prosentteja. Tehoportaat pitäisi olla selkeästi näkyvissä. Kuittausnappi tarvitaan. Liukukytkin voi auttaa havaitsemaan pilkkuvirheitä. Tehonnostogradientti?	Power and reactive power can't be set with a slider. Actual kW values should be used instead of percentage values. Execution button is needed for starting the power set-up. Possibility for setting the numerical value is needed, tenfold errors should be avoided.	2	Workload	Power steps needed in testing the system could be presented as buttons. Arrow buttons for fine-tuning the value could be added next to the numerical display. Execution button can be added.
5	Erilaista ja eriarvoista informaatiota samassa paikassa, hälytyksiä ja normaalia tietoa.	Unequal information (alarms, normal info) shouldn't be presented within the same frame.	2	Observability, failure management	Alarms and normal information could be divided into their own frames.
6	Näkyykö moottorin käyntitieto muusta kuin kierrosnopeudesta.	Indicating that diesel is running should be made easy.	2	Observability	Status text could be added next to the graphical representation of the diesel generator.

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ID	User finding	Change request	Priority	Related guidelines	Design suggestion
7	Samoja mittauksia ja arvoja monessa kohdassa, voisiko keskittää.	Same information shouldn't be presented in multiple places within one display.	2	Observability, workload	Duplicate values in the measurements frame (Mittaukset) can be removed. Other values could be moved into the frames containing related information.
8	Käynnistysvalmius pitää nähdä ensimmäisenä, miksi on keskellä.	Indication for if the diesel generator is ready for starting or not should be the first thing for the operator to see and clearly visible.	2	Observability, workload	Ready-for-starting frame could be moved to the upper left corner of the display.
9	Toisiinsa liittyvien kokonaisuuksien esittäminen saman kehyksen sisällä (esim. päänäytöllä tahdistustiedot, ilmastointinäytöllä puhaltimet ja termostaatit).	Information related to synchronizing should be combined within one frame.	2	Observability, workload	Synchronizing meters and control buttons could be combined within one bigger frame.
10	Dieselgeneraattorin käynnistys- ja pysäytysnapit eivät löydy.	Buttons for starting and stopping the diesel should be clearly visible.	2	Observability, workload	Location of the buttons can be reconsidered.

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ID	User finding	Change request	Priority	Related guidelines	Design suggestion
11	Tehon voisi esittää kuvana.	Power should be represented graphically instead of just a numerical value.	5	Observability	A trend or some other indicator could be added.
12	Olisi hyvä olla ajastin sille kauanko on ollut tyhjäkäynnillä.	Timer to indicate for how long the diesel generator has been running without load should be presented.	5	Observability	To be checked if this kind of information is available and possible to present in the user interface.
13	Virrat pitäisi olla eri vaiheiden mukaan eikä R, S, T.	Currents should be named 1, 2 and 3 instead of R, S, T.	0	Observability	To be checked.
14	Käynnistys varalle, tarkoittaako tyhjäkäyntiä?	"Käynnistys varalle" (Standby start-up) should be named "Tyhjäkäynti" (No-load operation).	0	Observability	To be checked.
		Subsystem display			
15	Käynnistysilmanpaineen oloarvo puuttuu, käynnistys- ja pysäytyspaine sellaisenaan tarpeettomia.	Current air pressure should be presented. Starting and stopping pressure don't need to be presented as such.	1	Observability	Current air pressure will be presented instead of starting and stopping pressure.

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ID	User finding	Change request	Priority	Related guidelines	Design suggestion
16	Apujäähdytysvesisäiliön pinnankorkeus meriveden yhteydessä, tulisi olla apuveden muiden tietojen kanssa.	Level of auxiliary cooling water container (Apujäähdytysvesisäiliön pinnankorkeus) should be presented together with auxiliary water (Apuvesi) instead of sea water (Merivesi).	1	Observability, workload	Level will be presented the same way as with jacket water (Vaippavesi) and removed from the sea water frame.
17	Komponenttien nimeäminen (esim. “täyttöpumppu” ->“päiväöljysäiliön täyttöpumppu”).	Components should be named unambiguously (e.g. “Täyttöpumppu” ->“Päiväöljysäiliön täyttöpumppu”).	2	Observability	Component names can be checked and changed if needed.
18	Pakokaasujen lämpötila: ei näy selvästi minkä sylinterien välillä suurin ero on. Notaatio dTmax(8-1) herättää kysymyksiä. Otsikon pitäisi olla selvempi.	It should be clearly displayed between which cylinders the biggest temperature difference is. Frame header should indicate that temperature difference is presented in the frame instead of just temperatures of individual cylinders.	2	Observability	Header could be changed to “Pakokaasujen lämpötilat ja suurin lämpötilaero” (Exchange gas temperatures and the biggest temperature difference). Better indication for which cylinders are taking part in the biggest difference could be added.

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ID	User finding	Change request	Priority	Related guidelines	Design suggestion
19	Käämien lämpötilaero tarvitaan.	Temperature difference of the coils should be presented.	3	Observability	Same kind of indicator as for the cylinders could be added.
20	“Vuoto” epäselvä mitä tarkoittaa.	The meaning of “Vuoto” (leakage) should be better explained.	3	Observability	Could be renamed.
21	Useampi raja-arvo (käämien lämpötila) herättää kysymyksiä, normaalin yläraja tulkitaan toivotuksi arvoksi.	Normal and alarm limits should be presented more clearly (e.g. coil temperature).	3	Observability	Representation could be made clearer e.g. by adding a light green rectangle to indicate normal area.
22	Selkeämpi ryhmittely, ohjaukset omaksi kokonaisuudekseen erilleen muista.	Information should be better organized. Controls should be together and measurements together.	3	Observability, workload	Information can be reorganized.
23	Jokaisella apujärjestelmällä voisi olla oma näyttö, yhteisellä näytöllä tieto yleisemmällä tasolla.	Each subsystem could have their own displays, common display could be on a more general level.	5	Workload	Hierarchical displays could be considered. Menu display could present information on general level.
24	Mitä tarkoittaa meriveden paine pulpetissa?	The meaning of “Meriveden paine pulpetissa” is not clear.	0	Observability	To be checked.

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ID	User finding	Change request	Priority	Related guidelines	Design suggestion
25	Tarvitseeko eri sylinteriryhmien lämpötilaeroa verrata ristiin?	Temperature difference between cylinder groups should be presented.	0	Observability	To be checked.
		Air-conditioning display			
26	Missä on termostaatin asetusarvo?	Set point of thermostats should be visible.	3	Observability	Set point could be added.
27	Puhaltimista pitäisi pystyä käyntitiedosta erottamaan ollaanko manuaalilla vai automaatilla.	It should be clearly indicated if a fan is running under manual control instead of automatic control.	3	Observability, failure management	Text MAN could be added to the fan symbol when running under manual control.
28	Toisiinsa liittyvien kokonaisuuksien esittäminen saman kehyksen sisällä (esim. Päänäytöllä tahdistustiedot, Ilmastointinäytöllä puhaltimet ja termostaatit).	Fans and thermostats related to each other should be presented within the same frame.	4	Observability, workload	Frames could be added.
29	Tieto puhaltimien käynnistysrajoista voisi olla näkyvissä.	Starting temperatures of the fans could be visible.	4	Observability	Indication for the starting temperatures (e.g. lines from fan symbols to temperature limits) could be added.

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ID	User finding	Change request	Priority	Related guidelines	Design suggestion
30	Merivesipumpun pitäisi näkyä ilmastointinäytöllä.	Sea water pump should be presented on the air-conditioning display.	4	Workload	Sea water pump could be added on the display.
		Ready-for-starting display			
31	Diesel ei käy (tuplanegaatio) herättää kysymyksiä, jotkut tulkitsevat automatiikkaviaksi.	The situation where the diesel generator is already running (n >320 rpm) should be clearly indicated.	2	Observability	A third option Diesel generator running (Dieselgeneraattori käy) could be added to the right-hand side of the display.
		All logic displays			
32	JA/TAI mieluummin loogisina operaattoreina, symboli on tuttu.	Symbols for logical operators should be used instead of text AND (JA)/OR (TAI).	2	Observability	Symbols can be used instead of text.
33	Harmaa lamppu on hassu.	Grey lamps shouldn't be used.	3	Observability	Lamp colours could be changed.
34	Plusmerkki herättää kysymyksiä.	Plus sign shouldn't be used in the connection square.	3	Observability	Plus sign could be removed.

C Rejected user findings

Rejected user findings and reasons for rejection are presented in Table 7.

Table 7: Rejected user findings.

ID	User finding	Reason for rejection
35	The term "VÄLI" is unclear within the synchronizing selection frame (Main display).	The term is the same that is used by Fortum. Means "välikatkaisija" (grid breaker).
36	Components should be situated as they are in the flowchart of the process (Subsystem display).	Conflict with change request 24. Separate presentations will be used as there is not enough knowledge of the process and, during user evaluation, all required information was easily found by the test users despite the lack of flowchart-like presentation.
37	Double negation "No fault" (Häiriö ei voimassa) is disturbing (Ready-for-starting display).	No use to change the whole logic. Readiness for starting is a positive thing so statements are indicating the positive thing.
38	Some alarms are triggered in all situations, some only when the diesel generator is running. Should be somehow organized?	Was not considered important by the test users pointing out the fact. Not enough knowledge to fix.