Operator Experiences on Working in Screen-Based Control Rooms

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Abstract – *This paper introduces the results of two interview studies carried out in Finland in four conventional power plants and one nuclear power plant. The aim of the studies was to gather data on user experiences on the effects of control room modernizations and digital control room technology on operator work. Since the number of completed digitalization projects in nuclear power plants is small supplementary information was gathered by interviewing operators in conventional power plants. Our results suggest that even though the modernization processes have been success stories, they have created new challenges for operator personnel. Examples of these challenges are increased requirements for competence and collaboration, problems in trust calibration and development of awareness of the process state. Some major differences in the digitalization of human-system interfaces between conventional and nuclear power plants were discussed.*

I. INTRODUCTION

This paper presents the results of two separate interview studies carried out in five power plants in Finland. The aim for both of the studies was to gather data on user experiences regarding work in digitalized screen-based control rooms. Another objective was to study the effects of control room technology changes on operator work.

The studies are part of a larger research project in which a method for the evaluation of HSIs (human-system interfaces) is developed. The evaluation method considers not only the immediate changes in human performance that might be expected after a technology change, but also the more profound significance of the change e.g. how does the new tool affect the operators' work practices and development of professional skills. The central aim of the interview study was to increase understanding on the effects of both modernization processes and screen-based control room technology on operator work, and gather knowledge of what kind of issues should be considered in the HSI evaluation of control rooms from the point of view of operators.

The motivation to carry out the research project is that Finnish nuclear power plants are currently undergoing control room modernization during which most of the hard-wired user interfaces are replaced with digital screen-based technology. In such a regulated domain of power production it is important to be fully aware of all the possible effects of the technology change and its potential safety implications. The interview study was also motivated by lack of data on the effects of control room modernization on operator work.

Control room technology has dramatically changed over the last 5-10 years as the old technology consisting of wall and desk panels has been replaced with computer-based technology. Most important general consequences of the digitalization of control rooms have been listed by O'Hara [1] and Pirus [2]: interaction with soft control method, increase in data availability to the operators, increase in data integration, hierarchical process representation instead of sequential, improved alarm management, computerized procedures, etc.

It is often claimed that a change from analogue control room technology to digital one has an impact on the operator work. Typical effects caused by new technology are e.g. the following: small display space for

information presentation introduces keyhole effect [3], soft control increases secondary tasks ([2], [3]), increased understanding of the automatic functions is required [1], and soft control requires conscious development of co-operation and communication practices [4].

II. METHOD

The results presented here are based on two separate interview studies. The first one was carried out in four conventional power plants (A - D) the control rooms of which were implemented partly or fully with screen based technology. The second study was conducted at a nuclear power plant (NPP) where the automation of the turbine side had recently been upgraded. Thus also the control room technology was partly screen based. The two data sets were analyzed separately because that allows us to make comparisons between the conventional plants and the NPP. Possible differences between the conventional plants and the NPP are emphasized in the following sections.

The interview method was a semi-structured interview. In the plants A-D one person was interviewed at a time and in the NPP a group interview was carried out. We had predefined the interview themes as follows: changes that had taken place in control room technology, operators' tasks, operating tools, and co-operation. More precisely we wanted to find out what kinds of changes had been carried out in the plants and how did the operators now in the new situation experience their work. E.g. what did they consider their core task, what are the main challenges in the work, and how the work is divided within the crew. We were also interested in the long term effects: e.g. how long it took to learn the new system, how does the feeling of control develop, and how do the new tools support the different operator roles and tasks. All the interviews were recorded and transcribed and analyzed to meet the demands of the research questions.

In the studies altogether 28 power plant operators were interviewed. Some operators had only little work experience (1.5 - 2 yrs) but others had worked over 20 years in the plant. In the conventional plants the interviewees were all operators but in the NPP also a maintenance person and a trainer participated.

Control room operators of five utilities were interviewed in the present study. The plants were chosen according to availability and the technology used in the control rooms. Plants A, B, C, and D are conventional power plants and the NPP is the nuclear power plant. Plants A and C had fully screen based control rooms. C had originally been implemented with digital technology and A's control room had recently been fully digitalized. B and D had hybrid control rooms. In plant B operations were mainly conducted with soft control although there was an analogue wall panel and a desk for performing operations on some auxiliary systems. In plant D analogue technology was still largely used for both monitoring and control purposes. All the plants had hard wired emergency systems. In the NPP the turbine systems all but one (feed water system) had recently been modernized. The reactor systems had remained analogue. Thus half of the crew works with screen-based and half with conventional technology.

III. RESULTS

III.A. Working in Screen-Based Control Rooms

III.A.I. Effects of the Increased Level of Automation

The rise in the degree of automation had caused changes in the work as well as in the demands on operator skills. In general, the content of the work in modernized control rooms had changed from manual process operations more to supervision of the automation. However, especially the operators of the conventional power plants claimed that the increased automation had not reduced the need of knowing how to perform operations manually in case the automation fails. The ability to operate manually was still seen as an inseparable part of professional skills, but nowadays the operators also have to master the functioning of the automation.

Some operators working in hybrid control rooms said that the modernization had increased the amount of work. Firstly, the operators have to maintain the skills of operating both analogue and digital user interfaces, and secondly, if there are parallel information sources, the operators have to monitor all of them. In addition, control room operators had taken responsibility of some of the duties of field operators when measurements had been transferred from the field to the control room.

In the conventional power plants the higher level of automation had made it possible to reduce the number of operators and broaden the scope of responsibilities of an individual operator. In conventional power plants A, B, and C, only one operator was now responsible for the monitoring and operating of the whole plant (or unit), whereas before the modernization there were two-three operators each responsible for a specific part of the plant (e.g. the turbine or the boiler). Thus, in the upgraded control room the operators had to master a larger part of the process than before the modernization.

Although the increased level of automation had made new demands on operator skills and knowledge, the general opinion was that operators had become more effective in dealing with their work. The main reason seemed to be that there was a lot more information available in the control room than before and the information was more reliable. The increased amount of information had made it possible to respond to alarms and diagnose faults more quickly than before. Also it was said that the functioning of the automation was more visible

and feedback from the automation system to the operator had improved because of electronic logic diagrams, sequence displays and electronic instructions.

When asked about trust in automation, the operators said that they are bound to rely on automation because using manual control continuously is not an effective way of working even if there would be a possibility to do so. Since the automation has been working reliably there are good reasons to trust on it, although careful monitoring of the automation system is needed.

In general, the operators said that the new digital automation is more reliable than the old analogous system. Although the operators had had doubts about the new system before the modernization the small number of disturbances in the functioning of the system had confirmed that the system is reliable and working well. Operators' trust on automation guides their reliance on automation [5]. Based on the interviews, reliance on automation relates also to each operator's ability to trust his/her own skills, level of understanding of the process, personal attitude and work practices. However, it takes time before an operator learns to trust him/herself as a user of the system.

Based on the interview data there were not many signs of over-trust on automation, however there seems to be some differences in how actively the operators monitor the functioning of the automation: some operators put more emphasis on alarms whereas other operators emphasize more the importance of anticipation and active monitoring.

III.A.II. Gaining Situational Understanding of the Process State

The operators gained understanding of the process state by navigating through the displays, monitoring the most important process parameters, and by checking the alarm list. In plants B and D where the control rooms were equipped both with analogous and digital systems there were some differences in how the operators exploited the parallel information sources. In plant B the operators used almost solely the computer system because of its more extensive information content. In contrast in plant D the operators often used both information sources. The analogous equipment had an important role especially during shift turnovers in gaining overview of the plant's current state and during disturbance situations.

Because of the small viewing area of computer screens, the operators only can get a glimpse of the process knowledge at a time [6]. Also they have to remember what information and controls are available in the information system. Our results suggest that the operators typically do not blame the system for the failures of remembering information, but they think that it is a part of their professional skills to find information fast and fluently. In general, the operators claimed that they are able to find the right information easily, although occasionally it might take some time. However, after long vacations of several weeks it might be difficult to remember where a particular piece of information can be found. To overcome this many operators had developed a strategy for refreshing their memory and for keeping up their ability to act quickly when needed: they navigated through all the displays regularly, often in every shift.

In connection to the keyhole-effect, as O'Hara and Brown [6] have said operators often prefer parallel information presentation instead of serial and also, that operators are reluctant to perform interface management tasks especially during high workload situations. Based on the interview data particularly many of the older operators preferred the analogous wall panels and desks because it is possible to get an overview of the whole process at a glance without navigating through a lot of displays. The operators often tried to imitate the spatially dedicated analogous system by placing the displays so that parts of the process next to each other were located on adjacent monitors. Also, many operators reserved a couple of monitors for certain displays and did not use those monitors for any other purpose. By this way a particular piece of information can always be found at the same place and is not covered by other displays. However, these arrangements were possible only if there were enough monitors in the first place.

According to the operators' answers concerning process overview the keyhole effect was not very significant in normal situations. The majority of the operators said that in most of the cases they can maintain understanding of the process state despite the limited viewing area by keeping the most important process diagrams and trends at sight. Still, some of the operators admitted that in certain situations (e.g. during start-ups) they are bound to leave some parts of the running plant outside monitoring.

Operators appreciated the flexibility of the computer based tools (see also [7]) which provided the possibilities of tailoring the user interface according to their needs e.g. by selecting which displays to use in different situations and where to place them as well as by creating trend graphics of important parameters by themselves. It was thought important that the operators are allowed to decide by themselves which displays to use and that operators should have permission to tailor the user interface also in the future.

There were contradictory opinions about the suitable amount of monitors: some operators said that about five monitors is enough and that it is difficult to observe more, whereas other operators would like to have as many as 12 monitors so that there would not be that much need of continuously changing displays. Some operators were also hoping for bigger displays. On a large display it would be possible to have more extensive process displays as

breaking down the process onto several displays deteriorates the possibility to gain process overview.

The majority of operators did not see that there was overload of information, except during disturbances when the alarm list is filled with information and the most essential information may be difficult to find. Therefore many operators desired for improvements in the prioritization of alarms. Generally the operators said that the density of information could be high on the displays, and there could be as much information as possible on the process diagrams, provided that the displays remain uncluttered and well-structured. It seems that new technology could be applied to a greater extent in the visualization of information. One good example of a graphical presentation style promoting perceptivity was the use of bar graphs in tank level indication. However, other visualization techniques that could promote the comprehension and memorization of complex information are not utilized to a great extent.

Together with other information systems large screen displays were used in monitoring the state of the process in conventional power plants A and C and the NPP. In the conventional power plant A the operators used the large screen actively in monitoring alarms and changes in some of the most important parameters. In plant C two of the three large screen displays had been broken for several years. The broken displays had not been replaced with new ones because it was thought that the costs of their repair or replacement would be higher than their benefits for operators. In the NPP the large screen display was intended to be used by the turbine operator but based on the opinions of the operators it would be more useful for the shift supervisor especially during disturbances. The main reason for the turbine operators not to use the large screen display was that the display was placed too high above the ground. However, even at its present location the overall display was thought useful for the other members of the crew who can now follow from distance what is happening on the turbine plant. Especially it was useful for the reactor operator who did not have any other way of getting information from the turbine side other than asking the turbine operator to tell what he/she wants to know. Also at the conventional power plants A and C the possibility to observe the state of the plant from the back of the control room was often mentioned as an advantage of the large screen display.

The role and the practice of using the large screen display was not very clear in any of the power plants. Based on the interview data the operators do not want to use the large screen for operations. However, during simulator training the large screen could be used for teaching purposes, since operations can be visualized at the same time for the whole crew. Because the operators don't seem to be willing to change the content of the large screens very often, it should be considered if the content of the large screen could be tailored for different operational situations e.g. normal power operation and start-ups. Also it is worthwhile to consider who should be in charge of using the large screen, e.g. should it be used mainly by the shift supervisor, as was suggested by the NPP operators. Large screen displays can promote crews' shared understanding of the process state but its role in co-operation could be developed even further by bringing up its possibilities during training.

III.A.III. Acquiring and Maintaining General Process Knowledge

Process knowledge is necessary for being able to perform operations, for seeing if automation is working properly, and for developing an appropriate trust in automation. The operators emphasized the need to know the effects of operations on the process and the constraints of the process equipment to be able to operate safely and efficiently.

In the conventional power plant C all control room operators worked regularly also on the field. Compared to others they had the best opportunity of keeping up process knowledge e.g. about where the equipment are located etc. In other power plants the operators had developed different ways of maintaining process knowledge. For example, the operators who could choose between using either analogue or digital controls sometimes intentionally carried out operations manually for the sake of remembering how the system works. Especially for the NPP operators the possibilities to visit field were quite limited. For them, regular training was an important means of keeping up process knowledge.

Many operators said that there is no difference between the analogous and digital systems in respect of how well they support operators in developing process knowledge. With the screen-based user interface alone it is not possible to acquire thorough understanding of the process, but training and experience from working in the field is required. Some operators said that it may be easier to get an overview of the process with the digital system since the way the process is presented matches the actual physical layout of the process more accurately on displays than on wall and desk panels. In contrast, others said that with the less automated analogous systems the operators learn more easily how the system works since they have to perform more operations by themselves.

III.A.IV. Navigation and Performing Operations

Changes in secondary task are hard to discover by interview method. Still, some results concerning experiences on using soft control, ease of learning to use the system and problems caused by the new system were found.

The operators' opinions about the ease of using digital user interface were contradictory. Most of them

claimed that browsing through the displays and using a mouse was not problematic and it is quite easy to learn to use soft controls as well as to navigate in the system. It was said that the digital interface allows you to concentrate on the primary task (i.e. monitoring) instead of the secondary (i.e. interface management). In contrast, with the analogous user interface it may be difficult to monitor what is happening in other parts of the process while pressing a button to perform an operation. On the other hand, some operators mentioned that they had had, and still had, difficulties with the new interface. They also said that the process seemed more tangible when using analogue devices.

Although the operators of the conventional power plants claimed that with the digital user interface navigation and performing operations with soft-control was not time-consuming, they, however, admitted than in panic situations they rather use hard-wired controls, in part because they are accustomed to do it in that way, but also because the hard-wired controls were easily reachable compared to soft-control the use of which requires a lot of navigating in the browser.

When using soft control the controls of a particular process component are typically not always at the same location in comparison with the analogous wall panels and desks where the controls are spatially dedicated. Although there had not been problems the operators of the NPP saw a possible threat of maneuvering wrong components as e.g. the symbols of the pumps always appear the same independently of the particular device. In the conventional power plants there had been some problems when the operators had confused about displays and performed operations on the wrong process components.

According to the NPP trainer older operators are more uncertain in using a mouse in performing operations than younger operators due to less experience in using computers. This had been taken into account by offering more training to those in need of it. Some of the reactor operators of the NPP said that they feel uncertain about their abilities of performing operations on the turbine side of the plant. This is a difference to the situation before with the analogous user interface when the reactor operators knew well also the turbine controls. The upgrade had affected the operators' relationships with each other. The role of the turbine operator in solving problems on the turbine side was said to be somewhat bigger than before.

The difference between the NPP and the conventional power plants was the amount and methods of training of the use of the new HSI. At the NPP the operators participated several times in simulator training whereas at the conventional power plants training was mainly executed with a master-apprentice method in control rooms. The training of soft control seems to be more systematic and thorough in the NPP, and even if there are no differences in how well the operators in different kind of power plants learn to use the soft controls, the amount of training influences the self-confidence of the operators as users of the system.

III.A.V. Co-operation, Roles, and Communication

In the conventional power plants new ways of presenting information and increased level of automation had made it possible to divide work in new and flexible ways. The operators working in fully digitalized control rooms were able to divide tasks as they wanted and they could assist the other operators due to the possibility of seeing the same displays. Also field operators and the shift supervisor participated occasionally in operations but it was seen essential that the operators had the overall control of the process. At the NPP no such changes in roles and responsibilities had taken place.

Interestingly from the viewpoint of co-operation the operators working in fully digitalized control rooms claimed that nowadays it is easier than before to know exactly what the other operators are doing by calling the same displays they are using. Before, one could only assume roughly what the others were doing when seeing what panels they used. Also, one operator described the feeling of social relatedness being nowadays higher than before the modernization because the operators are sitting more close to each other.

In contradiction to the results gained by Roth and O'Hara [8] considering the reduction of the amount of communication due to digital user interfaces, the general opinion of the operators was that there had not been significant changes in the amount of communication. For example, the need to tell others what you are about to do had not vanished. However, there had been some changes in the type and content of communication and co-operation. It was told that before the modernization the operators more often gathered together around a panel or desk to discuss the possible causes of group alarms. Nowadays, when the alarms are more accurate there is no need to discuss the reasons of disturbances to same extent. Also the need to come together in one place had reduced. Although the amount and content of communication was not affected by the type of the user interface the NPP operators saw that the amount of communication could be generally higher and that the issue should be addressed during training.

III.A.VI. Learning the New System and Training

According to the operators the length of the learning time varied from a couple of months to one and half years depending on previous work experience. After learning the functioning of the process the most difficult thing to learn was said to be related to finding information from the system. The operators who had been using the

analogous system before said that it takes some time to unlearn the old system and instead to learn how to perform the same actions with the new user interface. In this sense it is somewhat simpler for the inexperienced operators to learn the new system.

Sufficient amount of training is important because putting the operators too early in charge of the controlling of the plant may lead to stress due to lack of self-confidence and fear of mistakes. The operators said that trust in own skills is gained only by performing operations by oneself, not just by seeing how other operators or trainers do it. Participating in start-ups, shutdowns or testing procedures was seen very useful and informative in order to get hands-on experience.

Acquiring and maintaining knowledge of rare events seemed to be a problem for the operators. The NPP operators were the only ones who had a training simulator in use, and they said that they would like to have more training related to disturbance scenarios. Also many of the operators of the conventional power plants desired to have training simulators to be able to rehearse complex situations. Many operators had developed other practices for maintaining knowledge and skills related to rare events. Many had the habit of revising procedures. Also reading error reports and discussing challenging situations together with experienced operators were seen as ways of learning and rehearsing.

Uncertainty and hesitation is sometimes caused by inconsistencies between the systems, e.g. different kinds of symbols and colors. The vast amount of information systems was said to be a real challenge for learning as the operators have to master sometimes even more than ten different systems. Introducing new digital systems may add to overall complexity as the operators have to understand the functioning of several systems and know their limitations and capabilities [9].

III.B. Operators' Experiences on Modernization Processes

There had not been major changes in the control rooms of the conventional power plants during the passed five years. This means that the first stumbling blocks had been passed and that most of the plant personnel's initial resistance to change had vanished. In the nuclear power plant the change in technology was more recent and the modernization process was partly still in progress.

In the nuclear power plant the changes had been somewhat more extensive than in the conventional power plants. E.g. electronic disturbance operating instructions had been taken into use only in the nuclear power plant. Also some of the analogous systems, e.g. the user interfaces of some auxiliary systems, had been left unchanged in the conventional power plants. Thus, the operators of the conventional power plants had to master even more different kinds of systems and tools than the NPP operators.

It seems that compared to the operators of the conventional power plants the operators of the nuclear power plant were generally more satisfied with the conduction of the modernization process. A significant difference between the modernizations of the different types of power plants was the amount and methods of training related to the new HSI and its correct use. The training had been somewhat more extensive for the operators of the nuclear power plant, understandably because of the possibility to use simulator in training and because of safety requirements. Despite the extensive training the NPP operators were willing to participate in even more training to become more confident users of the new digitalized system.

Another difference between the modernization processes seemed to be the amount of operator involvement in the process. In the nuclear power plant the operators had had the chance to give their opinions of design issues all the time during the modernization. Also the operators of the conventional power plants had had the possibility to influence the design by suggesting improvements but it had happened perhaps more after the modernization process than during it. Some of the operators hoped for an opportunity to explore different kinds of user interface concepts to be able to compare them. They said that it is difficult to judge the design conceptions when you do not know of other alternatives.

Based on the interview data there had not been a lot of resistance to change in any of the power plants. The operators had been uncertain about the superiority of the new system compared to the old system, but after the operators had got accustomed with the new system none of them would have wanted to return to the old analogous system anymore. The same phenomenon has been noted by O'Hara et al. [9].

Some of the operators said that they usually have high expectations of the new systems and the improvements they bring. The new systems have to be better than the old ones, as otherwise there would be no point to upgrade the HSI in the first place. If the outcome of the modernization process turns out to be a disappointment, it has consequences on operators' trust on the new tools and attitudes towards working. It is important to tell the operators what kind of changes are about to be realized and how do they influence their work. Also, they should have an opportunity to get involved in the design process because they are the best experts of their work.

III.C. Operator-Oriented Modernization Process

Operators' involvement in the design of HSI is beneficial since it reduces potential resistance to change. Also, it gives designers insight of the characteristics of

process control work in a particular power plant. Based on the results of this study an important factor influencing the NPP operators' opinions related to the display design was that they had had a representative in the designer team. The person was said to be very competent and the operators were confident that he has taken the operators' point of view into account as well as possible. The operators had been very interested in seeing design sketches. Keeping track on the progress of the design helps the operators to prepare themselves for the change.

The operators of the nuclear power plant were asked if there were things that should have been done differently during the modernization process. The operators mentioned that it would perhaps be easier for the operators if the whole control room would be modernized at a time. The problem of partial modernizations is the high number of different kinds of systems which adds on the complexity of work. Also, when some of the members of the crew are using digital user interfaces and others are using analogous user interfaces, the co-operation is altered. Co-operation and communication might deteriorate if new work practices are not developed. The operators thought that it is of high importance that the separate digital systems resemble each other as much as possible, i.e. that the way of presenting information is consistent throughout the systems.

If the modernization process is conducted in stages, training should be provided for all control room operators, not just the ones that will be using the new digital systems. The introduction of new systems will affect the crew and its performance as a whole, which is why no one should be left without sufficient training. The sufficient amount of training depends on operator competence so there should be a possibility to participate in additional training sessions if needed. Each operator him/herself knows best when he/she feels confident enough about his/her skills as a user of the system. One option for providing more training might be a "mini-simulator" located in the control room. The operators of the nuclear power plant were hoping for having a "mini-simulator" where it would be possible to look at the displays (but not perform operations) whenever there is extra time.

In the NPP there had been positive experiences of taking the change of generation into account in planning of the conduction of the modernization process. Many of the experienced reactor operators are retiring fairly soon. Until retirement they can use the analogous user interface which they know well. The modernization of the reactor control system will be carried out after about five years. At this time the younger turbine operators, who already have experience on using the digitalized turbine control system, will take the places of the retired reactor operators. This is beneficial form the point of view of plant safety since the operators are already experienced in using digital HSI.

Modernization processes are constructed of many stages. Sub-projects that might seem separate (e.g. modernization of the main process control unit and the modernization of electronic procedures) but are somehow connected to each other might be difficult to piece together for the operators. This makes demands on the management of the modernization process. The connections between the projects should be described to the operators. Also, the projects should be scheduled in a way that the operators are not burdened under several projects at a time.

IV. CONCLUSIONS

All together 28 operators were interviewed in Finnish power plants that have recently modernized and upgraded their automation systems and human-system interfaces. Some of the lessons learned from these interviews are the following:

1) The requirements for competence are increasing with the increase of automation.
2) The calibration of operators' trust to the actual system reliability takes time.
3) The amount of available process knowledge has increased, providing faster diagnosing of failures.
4) Due to introduction of desktop-based workstations and removal of old analog human-system interfaces, it has become more complicated to get an instantaneous overview of the process state.
5) Flexibility and tailorability of the new user interface are appreciated.
6) The role and the practice of usage of large screen displays should be considered thoroughly in power plants. Otherwise, the technology might not be used to its full potential.
7) With the digital control room upgrades, the importance of training has substantially increased.
8) New technology allows for more flexible roles and responsibilities, but these possibilities are not necessarily put into practice.
9) The introduction of desktop-based workstations may change communication and collaboration between operators.

Some major differences between the modernization processes in the conventional power plants and nuclear power plants emerged in the discussions. First, because of the complexity of nuclear power process and potential high risks associated with nuclear technology the modernization process seems to be better controlled and managed in nuclear power plants. For example, training

programs are carefully planned, and the training itself is more extensive. Second, the introduction of new technology seems to cause less dramatic changes in roles and responsibilities in the nuclear field, since the typical aim is to keep the level of automation and the allocation of functions between personnel and automation systems constant. Third, operators play a more active role in the modernization process in the nuclear field: they often actively participate in the design process, and they have opportunities to present suggestions for improvements in the different phases of the project

In general, our findings are consistent with several recent reviews on experiences and lessons with control room upgrades (e.g. [9], [10]). They all point to the challenges in managing the modernization process and developing new human-system interfaces in a user-centered way.

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