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Lessons Learned From Case Study On Procedural Turbine Automatics In Nuclear Industry

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Abstract

The nuclear industry is moving towards higher degrees of automation to improve efficiency and safety. Lessons learned from other safety-critical industries indicate that such efforts are not always successful, potentially causing undesired events and accidents resulting from human-automation interaction failures. A key effort for building relevant knowledge in this area is to learn from practical cases where new automation technologies or concepts have been introduced. This paper describes a user-centred case study on procedure-based turbine automatics in operation by Nordic nuclear powerplants, identifying user experience and potential design improvements. The study reveals both positive and negative aspects of the implemented design and user experiences. The main contributions of this paper are: i) practical lessons learned on human-automation interaction and human-system interface design and, ii) describing and discussing an operative reference case, potentially useful for researchers, developers, and users of future procedure-based automation for process control.

Keywords: human factors, human-automation interaction, computer-based procedures, procedural automation, control room design, human system interfaces, process control

1. Introduction

There is a considerable drive across all safety-oriented industries to increase the degree of automation to improve efficiency and safety. Lowering operator workload, reduce risk of human error, automating tasks that are difficult for humans to do, or lowering the number of people needed to run a facility or system are common objectives. Regardless of automation level human operators remain a crucial part of these systems and are – as a minimum – expected to handle unforeseen events, acting as a last line-of-defence against failures. Several incidents and accidents have occurred in recent years related to poor human-automation interaction, particularly in the aviation industry – refer e.g. the recent BOEING 737 MAX accidents (National Transportation Safety Board, 2019). Thus, a key challenge when designing such systems is to promote performance in contexts that require humans to interact with automatic systems, ensuring that the joint team is successful in achieving common goals.

In this paper we address procedure-based automation for nuclear process control. Since most areas of operating a nuclear powerplant are governed by procedures, efforts are being made to support and improve procedural work. Some plants have introduced Computer Operated Procedure Systems – COPS (also referred to as Computer Based Procedures – CBP, or Computerized Procedure Systems – CPS). The industry commonly distinguishes between different types of COPS capabilities, where the most advanced integrate useful process information with procedure controls and can even perform series of control tasks without the need for operator assistance. This is often referred to as procedure-based automation. COPS are distinguished from safety protection systems where automatic shut-down and/or isolation "procedures" are triggered.

As procedure-based automation is increasingly being utilized there is both the need and opportunity to learn from operational experience. One such example can be found in Nordic nuclear powerplants where the procedural tasks involved in planned start-up and shut-down of the Turbine Generator are automated, typically performed during refuelling outages. This paper describes a case study that IFE performed in 2021-22 on the so-called “Turbomat”. The study was a collaborative effort, funded by four Nordic powerplants, with two main objectives:

1) Identify current user experience with the Turbomat.
2) Make practical recommendations for improving it from a user perspective.

In this context, what was considered “practical” mainly relates to the amount of effort involved in making changes, either technical (e.g. control logics and Human System Interfaces (HSIs)) or operational (e.g. procedures and training).

This paper describes findings from these activities and discusses potential implications for the future design of procedure-based automation in this domain.

1.1. Theoretical background

From the field of human-automation interaction in safety-critical industries two topics in particular seem relevant for this case. The first relates to teamwork and the way automated systems work collaboratively with humans. For complex systems, there seem to be a growing acknowledgement that human-automation interaction is not limited to “who does what”, i.e., function allocation (Lee, 2018). Rather, automation may be viewed as a member of a joint human-machine team that have shared responsibility for system performance. The research questions are then focusing on how humans and automation should “get along together” (ibid.). In the article “Seven Deadly Myths of Autonomous Systems” Bradshaw et al. conclude: “Although continuing research to make machines more active, adaptive, and functional is essential, the point of increasing such proficiencies isn’t merely to make the machines more independent during times when unsupervised activity is desirable or necessary (autonomous), but also to make them more capable of sophisticated interdependent activity with people and other machines when such is required (teamwork)” (Bradshaw, Hoffman, Woods and Johnson, 2013, p. 7-8).

The second topic relates to what is commonly referred to as automation transparency (related terms are “observability” and “explainability”). Research suggests that enabling human operators to see what automation is doing and how it operates can increase trust and overall system performance (see for example Christoffersen and Woods, 2002). However, transparency efforts needs to be consciously directed. After studying effects of automation on human performance in the nuclear domain Skraaning and Jamieson concludes that “automation transparency appears to yield expected benefits for component-level automation, but caution is warranted in generalizing the design principle to agent-oriented automation” (Skraaning and Jamieson, 2019). Similarly, Bhaskara et al. concludes that “…there is emerging evidence to suggest that transparency can increase the accurate use of autonomous agents by human operators. However, evidence regarding which precise level of transparency yields the most accurate use of agents has been far from consistent.” (Bhaskara et al, 2020). As the degree of automation in the nuclear industry increases, key questions are related to *what* kind and level of transparency is most useful for users in different situations and case settings, and *how* it should be presented in the HSI to positively impact performance.

For procedural automation within nuclear process control there are several relevant industry guidelines, all governing COPS in general. A key review guideline is the “Computer-Based Procedure Systems: Basis and Human Factors Review Guidance” for the US regulatory NRC (O΄Hara, Higgins, Stubler and Kramer, 2000). There are also the design guidelines “IEEE Guide for Human Factors Applications of Computerized Operating Procedure Systems (COPS) at Nuclear Power Generating Stations and Other Nuclear Facilities (IEEE, 2022) and “Human Factors Guidance for Control Room and Digital Human-System Interface Design and Modification” (EPRI, 2015) which includes a chapter on COPS.

IEEE identifies three types of COPS implementations, where the third is the most capable in terms of functionality: “Type 3 systems include embedded soft controls that may be used to issue control commands to plant equipment. Type 3 systems may include automatic sequences of steps (i.e., procedure-based automation) that are determined to require limited operator oversight, and for which there are procedures and training that would allow the operator to perform the steps manually, if necessary or desired” (IEEE, 2022). A key focus in design guidance for type 3 COPS is making sure the human operator is in control of initiating and interrupting automated sequences, enabling them to assume manual control if desired or necessary, ensuring amongst other things proper placekeeping, mode and progress awareness, as well as offering troubleshooting aid in case of unintended interruptions.

2. Method

We will present this work organized in two studies. Study 1 involved an initial phase where we gathered information on the Turbomat system implementations at different plants and then conducted an experience review of each system (based on end-user interviews) the findings were processed through design analysis of the current systems based on the challenges identified in the interviews. Study 2 was built on the findings from Study 1. Here, a few design recommendations and prototypes were developed and tested with targeted users from each of the plants in sessions where we walked through the previously identified challenges and how they were addressed in each prototype, collecting feedback from the end-users.

An explorative, user-centred approach was chosen as the overarching methodological framework, and the research activities were organized in four main phases:

- Experience review of existing Turbomat control room solutions
- Exploration of possible improvement measures – prototype and mock-up development
- Evaluation/feedback sessions with end users and other stakeholders
- Summary and recommendations

A steering committee from the participating plants consisting of former operative staff and human factors personnel met regularly throughout the project to give input and to prioritize between topics that could be addressed.

2.1. Study 1

2.1.1. Procedure

We conducted semi-structured individual interviews with volunteer participants from five different control rooms. The interviews were performed online in 1-hour sessions.

2.1.2. Participants

Eight turbine operators, from five different control rooms were interviewed at this stage. All of them were male and had between 2 and 17 years of experience as turbine operators. Most had additional experience in other roles at the plant. We also interviewed three people in technical support roles.

2.2. Study 2

2.2.1. Procedure

We performed four group sessions, one with participants of each of the involved plants − two on video and two in-person. These were all held as informal, exploratory discussions/user tests, centering around a set of proposed design principles exemplified through mock-ups and semi-interactive prototypes (no simulators were used).

2.2.2. Participants

Eleven operators participated in the evaluation sessions (with an average of 11.5 years of experience in the nuclear industry, range between 1 and 41 years).

3. Results

3.1. Study 1

3.1.1. The Turbomat system design

While there were differences in the Human System Interfaces between the participating units, the overall control approach was similar. The system was utilised for running the turbine and associated auxiliary systems up and down, and its internal algorithms structured in sequences of steps and sub-steps, each characterized by preconditions, actions and end conditions. Stable plant states acted as milestones (hold-points) between sequences. A typical implementation consisted of around 6 sequences, 15-20 main steps and 50-70 sub-steps. Running up the turbine from standstill spans several operator shifts.

The user interface offered the ability to monitor current state and progression, and to select between three main modes / Levels of Automation (LOA) by manipulating two toggled choices: ON/OFF and MAN/AUTO.

1) ***Off*** (OFF+MAN) – no active guidance (status indications) or control commands are issued.
2) ***Guidance Operation*** (ON+MAN) – the system provides active progression status indication, but no control commands are issued.
3) ***Auto Operation*** (ON+AUTO) – progression status indications and control commands are issued.

The Turbomat system allows operators to dynamically adjust the mode in real-time during operation, but such adjustments were governed by plant operating procedures in all the participating plants. The operators could initiate a mode change at any time. The system would never increase LOA by itself, but during Auto Operation it could run into stop conditions causing it to interrupt the sequence and switch to Guidance Operation (e.g. if an order didn´t have the intended effect within a predefined time), or initiate an automatic run-back procedure to return to a previous hold-point (e.g. if an auxiliary turbine system fails).

In this paper we will focus on the most common digital HSI design, which consisted of a condition monitoring map outlining the sequence, the "current" position in the sequence implicitly being the lowest unfulfilled condition. This was visualized as a series of alarm "tiles" organized in the order of task sequence from turbine standstill to full power operation. In some ways this interface resembles a "progress bar" commonly found in other software. A principle sketch is shown in Figure 1.

Fig. 1. Principle sketch of the Turbomat interface. When it runs up the turbine it works sequentially from top left to bottom right.
(a) "Syncing" the Turbomat to the plant status highlights unmet primary conditions and determines its current position in the sequence as the lowest step with fully met conditions.
(b) The Turbomat working step 1 towards plant state (hold point) "Turning Gear" at the completion of step 2.
As automation activities progresses the conditions highlighted in yellow successively turns grey.

The automatic sequence is outlined in four columns: The left side displays so-called "primary conditions" indicating the preconditions for executing individual steps. In the middle the main steps are shown, highlighting the current position within the sequence. Further right are the sub-steps, called "secondary conditions". To the right are stable plant states (hold-points). All are organized in an alarm-style fashion, indicating alarming states in the context of full power operation.

Alarm tiles are a common interface element in nuclear control rooms, offering operators a spatially dedicated way of monitoring and detecting deviances across plant states. The Turbomat interface is designed so that no alarms should be lit during full power operations at the conclusion of the start-up procedure. Before putting the Turbomat in Auto mode the interface requires operators to "sync" it to the plant. Once in Auto it monitors only the sub-steps associated with the current step, as well as relevant stop/run-back conditions (ref Figure 1). The study did not include interviews with Turbomat designers, but this "selective monitoring" strategy have probably been chosen to minimize visual clutter during undisturbed progression.

Also, in most plants the Turbomat had originally been designed as an analogue panel with physical buttons and alarm tiles. Most plants had now digitalized it, and many digitalization efforts had resulted in a screen-based version strongly resembling the original panel design.

3.1.2. How the Turbomat was used

The Turbomat was used both for running the turbine up and down, but operators stated that it was most useful during start-up. Most plants used it in Guidance Operation during the earliest stages of the sequence, stating that this part of the procedure took a rather long time to execute (spanning several shifts) and they were afraid it unexpectedly would issue control actions or "run away" from them in this phase. Auto Operation was commonly used during the latest stages of the procedure. One unit never used it in Auto Operation at all, only in Guidance Operation. The experience review further indicates that the perceived usefulness of the Turbomat was mostly related to reducing risk of human errors and freeing up cognitive capacity for the turbine operator, and less related to increasing the efficiency of running up the turbine.

3.1.3. Overall positive findings

The at-a-glance overview of the entire sequence, preconditions, current mode and position that was provided by most versions of the Turbomat HSI was considered beneficial. Also, the ability to use the Turbomat both as a guiding tool during manual operations (Guidance Operation) and for performing actions on the plant (Auto Operation) was key to its perceived usefulness. The versions that didn´t or only partly offered this capability were critiqued for it.

Overall negative findings

Many operators were somewhat intimidated by the Turbomat. The user acceptance of the Turbomat was generally low. Several operators offered statements to the effect of "I am a bit afraid of what it is going to do to me". A range of usability issues found in many of the implementations added to the negative sentiment.

Surprising behaviour when changing from Manual or Guidance Operation to Auto Operation. While not typical, in certain situations users were somewhat unsure about where the Turbomat would start working the plant when put in Auto Operation. One concrete example was described where surprising commands had been issued. In this situation the confusion seems to originate from a combination of plant modifications, procedural changes and the Turbomat interface itself.

Issues with syncing the Turbomat sequence starting point to the overall plant start-up operating procedure. A related issue happens when performing the synchronization ("sync") feature (ref fig 1). The Turbomat will signal which step it is currently at, but some users would struggle if this step differs from what the overall plant operating procedure said it should start from, which reportedly happened quite frequently. Some users said that they would approach this by trying to force the Turbomat into a different step, which could allegedly be done unintuitively through "a lot of clicking".

Challenges associated with updating the Turbomat to match changes being made to operational procedures or the plant. Issues arise when the Turbomat is not properly updated according to operational or technical changes made to the plant over time. There could be economical, technical, or organizational reasons for this, but the end result was that the operators in some cases would implement vulnerable workarounds to be able to achieve their goals. In one plant this had led to at least one situation where undesired control commands had been issued by the Turbomat, which had also not been discovered until the following shift.

When the automatic sequence was interrupted, the Turbomat offered relatively little problem-solving support. The Turbomat is designed to stop the automatic sequence if sub-steps are not completed within a predefined time and stop/run back if certain conditions are not met. Time-outs would typically not be displayed, and in some versions stop-conditions were not displayed comprehensively, so users would need to reference Turbomat documentation in combination with information located in the control system interface to find the cause of the interruption. This is relatively time-consuming and considered a nuisance.

3.1.4. Discussion

We did not identify any clear violations of the COPS design guidance referred to in section 1.1. However, three characteristics of the Turbomat design and its use stood out to the IFE research team:

Alarm-driven visualization results in a complex user interface. The core visualization concept is built around progression of activities resulting in non-alarming conditions. The designers of the Turbomat have chosen to only display/monitor a subset of these alarms based on the situation, probably to avoid alarms saturating the interface during most of the run-up and run-down procedure. This design choice results in the need for "sync" and a very narrow scope of supervision during automatic step execution, ref fig 1. This also means that when users read the steps to understand the Turbomat´s planned behaviour they see the negative version of events – what should *not* be the case after actions are executed. While this approach is consistently applied it seems unusual from a user interface design point of view, and we suspected that this characteristic contributed to the low user acceptance.

The Turbomat offer limited adaptability to changing circumstances. The Turbomat allows some flexibility in that it is possible to use as a support when the steps are performed manually (Guidance Operation). However, users gave examples of situations where the rigid sequence of the Turbomat no longer was suited to how their plant needed to be operated. The user interface allows few user driven adjustments to the sequence that could have been useful, such as manually overriding steps, or monitor several sequential steps simultaneously to support parallel execution. Changes to the plant or procedures required the Turbomat to be redesigned, which led to temporary workarounds being put in place instead.

Rare usage adds to the challenge. Primary use of the Turbomat is for running the turbine up and down, which typically occurs during outage – approx. once a year. Individual operators may or may not be in contact with it in this period, depending on their shift rotation. If such a tool is not intuitive, extensive training will be required to secure adequate operator performance.

3.2. Study 2

3.2.1. Possible design measures

The researchers looked for measures that would reduce the perceived complexity of operating the Turbomat, reducing the risk of misunderstandings and making it easier and less intimidating to use. To a certain degree, measures were sought that were considered "practical" - i.e. minimizing the cost of making changes while still having the desired effect. To this end, ideas were discussed with technical support personnel. Key ideas are presented in the following:

Measure 1: Remove need to "sync" the Turbomat to the plant, allowing a continuous status monitoring across all modes. The IFE team wanted to explore how one might avoid the "sync" feature altogether as a strategy for reducing the confusion described above. One way of approaching this would be to continuously monitor and display process status in all LOAs, making it behave more similar to the progress bars one is familiar with from other software tools. This would mean challenging the current alarm-driven visualization and rather find a way of displaying status information suited for both normal and disturbance situations. To make this work, at least two new concepts may be required: 1) Ongoing status monitoring needs to contextually distinguish between expected and unexpected (alarming) states. The Turbomat should be able to determine which condition is expected based on the current position in the sequence. 2) Process conditions that are no longer relevant in the current step position should not result in an alarm. Some conditions are transitory, and their expected state will vary during sequence progression. See Figure 2 (left) for an example.

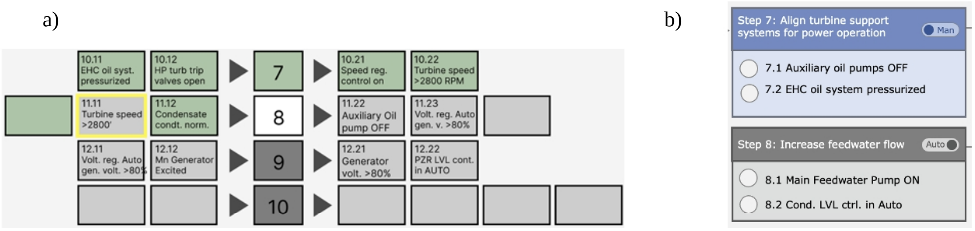

Fig. 2. (a) Remove need for sync. Principle sketch of an imagined interface that continuously monitors conditions, distinguishing between conditions that are met (green) and unmet (grey), and using alarm colour only for unexpected states (yellow outline); (b) Principle sketch illustrating an imagined mechanism for influencing automation behavior, in this case which steps to be performed manually or by automation.

Measure 2: Provide operators more ways to influence automation behaviour. In all versions the Turbomat itself determines the appropriate starting point based on its analysis of the required steps to reach the specified destination. It is possible that by allowing users to also specify the starting point, their sense of control and awareness of the automatic behaviour will be increased, and thus the potential for confusion reduced. Of course, the Turbomat should still alert or hinder operators from selecting undesired starting points from a process perspective. The potential for surprises could also be reduced by allowing operators a greater level of flexibility and control over automatic behaviour, such as "blocking out" individual sub steps or flagging them for manual operations or being able to influence set-points and alarm/time-out limits. See Figure 2 (right) for an example of how this might be displayed.

Measure 3: Offer better diagnostic support. Most versions of the Turbomat offer only a title associated with each sub-step. One Turbomat implementation went further: Logic signal diagrams, measurement points, control commands, and time- out specifications associated with each sub-step. This seemed to provide users with useful information used for manually executing the steps, but one could imagine the same information being useful for problem-solving in case of an unplanned sequence interruption, see Figure 3 right.

3.2.2. User feedback on possible design measures

Operator feedback on the three ideas discussed above is summarized below. The concepts were illustrated through mock-ups and semi-interactive prototypes to facilitate group discussions (examples shown in Figure 2 and 3). Given the fidelity of these mock-ups and the limited number of participants results are far from conclusive, but they provide a good indication of measures that could have a positive impact on performance.

Measure 1 - Remove need to "sync": All of the participating operators were positive to the idea of removing need to sync by always displaying Turbomat status, as described above. They felt that this might make it easier to get a good overview of the current situation without needing to interact with the system, while relevant alarms still could be displayed with proper salience. Also, displaying desired rather than undesired (alarming) states was the preferred design variation overall.

Measure 2 - Offer more ways of adapting automation behaviour: The idea of enabling operators to select start point for procedure execution was met with mixed feedback. The main concern was that this might introduce new opportunities for errors if steps were missed that needed to be completed. To succeed, proper guidance would need to be introduced to minimize this risk while still improving the ease of use of the tool. On the other hand, there was consensus among participants that being able to select certain steps for manual operation within the sequence (or "block out" steps that the automation should avoid doing) could be highly useful, and the added risk of errors was considered low.

Measure 3 - Offer more information useful for diagnostic support. There also seemed to be a consensus among the participants that more details could be highly beneficial for supporting problem solving. However, this should not be implemented at the expense of a good sequence overview, so several participants suggested that a good solution might be a two-screen setup complimenting the "progress tree" display with another that provides more details, such as logics and other step information. This idea is illustrated in Figure 3, and would allow users both to perform at-a-glance monitoring of the status and progress of the automated procedure, and at the same time have access to a more detailed view of steps, logics and stop conditions useful for monitoring, planning and troubleshooting. A two-screen setup would allow operators to perform both tasks simultaneously, which would allow them to always maintain situation awareness without needing to engage in HSI management tasks. The effectiveness of establishing a fixed, at-a-glance overview for ensuring proper situation awareness is consistent with related HSI research within complex, safety-critical industries.

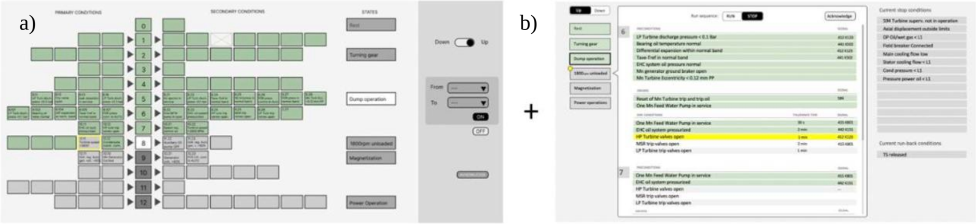

Fig. 3. User feedback points towards design improvements that combines ideas from two different concepts that were explored, illustrating a possible two-screen setup consisting of a fixed overview of procedure outline, current status and progress (a); and a more flexible display allowing on-demand details drill-down (b).

4. Implications beyond this case

While the Turbomat design does not seem to be in direct violation of any established guidance on procedural automation in the nuclear domain it still suffers from several issues that influence its performance negatively. These seem rooted in shortcomings related to teamwork and automation transparency consistent with the theory presented in section 1.1. From a purely engineering perspective, developing a procedure-based automation system might seem like a straight-forward matter of linear step execution, but this case illustrates some of the added complexities – and therefore necessary logics – involved in extensive, plant-wide procedure automation. The Turbomat relies heavily on continuous process monitoring for determining where to start working the plant, when to automatically interrupt procedure progress, or even run back to a previous step (which is not necessarily a reverse of the forward-oriented sequence). As the degree of automation increases in nuclear plants we should expect that the scope and complexity of procedural automation will increase along with it, resulting in the non-linear behaviour requirements described above. Based on this study it seem opportune to question whether design strategies that work well for simpler and shorter procedures are sufficient, or even valid, for longer and more complex ones. More research could be dedicated to this topic.

From a transparency-perspective we find it interesting that users of the Turbomat actively seek information about how it works in order to trust and collaborate effectively with it. For example, getting an overview of stop- and run-back conditions seem to help operators not only to troubleshoot during upsets, but also to understand the perimeter of the system´s capability during normal operation. They use this knowledge to direct their own control efforts accordingly, such as planning and performing manual control actions. Thus, making such information explicit and sufficiently salient in the interface could be a good idea. Also, this study suggests that visualizing automation activity (what does it *do* - the plan or “script” for task execution and automatic interventions) as well as its effect on the plant (what is the *result* of those activities, with an emphasis on safety) is both useful for operators. This study further suggests that separating the two in the HSI might be a good design strategy (illustrated in Figure 3). Learning more about this could be a good topic for further research.

From a teamwork perspective the study supports existing theory in this area, concluding that operators will likely benefit from (more) built-in flexibility and adaptability, and that accomplishing this without introducing new risks becomes a key HSI objective when designing such systems. This includes making procedural automation interfaces useful across different LOAs (not only the highest levels), as well as adaptable to changing conditions, such as plant and procedural modifications made over time. This includes making the HSI suited for different work-styles, such as combining manual and automatic execution. This study shows that operators may otherwise implement vulnerable workaround control strategies to get their job done, perhaps utilizing the system in ways it was not intended to.

The design of future procedural automation systems must also consider that operators´ information and interaction needs will likely change according to changes in operational concepts. The operators that participated in this study all wanted to be relatively hands-on, which is consistent with their current role as active participants during procedure execution. Moving towards higher degrees of automation – as future automation systems become more capable and operator roles change – operator needs might change which affect e.g. transparency requirements, as also suggested in the existing research referred in section 1.1.

5. Conclusion

This has been a qualitative study identifying current user experience and potential improvements to a nuclear procedure-based automation system. As the degree of automation continues to increase across safety-critical systems this is likely a factors that will impact overall performance. This study suggests that is not necessarily a straightforward task from a human-automation interaction perspective. The findings compliments and existing theory on effective human-automation interaction, and in particular address aspects related to teamwork and transparency. A reference case is provided that illustrates practical design examples and improvement areas that could be useful for developers and users of future automation systems. Even though this study was conducted in the context of process control in the nuclear industry, the lessons learned in regards to HSI design and human automation interaction are likely to be relevant for related industries and domains as well.

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