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Impact of Adaptive Automation for Supporting Operation in a Nuclear Power Plant. An Explorative Study

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The intrinsically complex operation of nuclear power plants can benefit from advances in technology. New forms of automation, exploiting an increasing availability of data in real time, integrating information from several sources, can adapt more effectively to dynamically varying situations, and with the help of smart interaction with the user could improve the human performance in many situations. One of those forms of automation, adaptive automation, could monitor and recognize significant situations and help in balancing the task distribution between the system and the operators with the goal of increasing performance. As for any type of automation, the introduction of this concept can fundamentally change the work processes and demand on the operators, therefore, its impact on the operators needs to be evaluated. The presented study explored the effects of a prototype of an adaptive system assisting an operator during a normal operating procedure in a nuclear power plant. The first results are encouraging, showing high user acceptance and generally positive feedback.

Keywords: adaptive automation, operation support, user study, human performance, computerized procedures, qualitative study.

1. Introduction

Automation has been part of the operation of nuclear power plants for many years, with advantages in efficiency and in safety but also with some drawbacks, like rigidity, low transparency, loss of skill, and boring tasks for operators. The availability of modern technology, offering real time access to huge amounts of information and enhanced processing capability, makes it possible to deliver a new type of automation, aiming at better efficiency, preserving, and possibly enhancing safety, and reducing the potential negative impact that more traditional automation is known to have (Bainbridge, 1992).

The new forms of automation can have different capabilities. One example is the ability to dedicate tasks to operators by monitoring plant state in real time. So that tasks can be dynamically assigned to automation or to operators, depending on changes in the environment or the operating conditions. We refer to this ability as adaptive automation. The main expected advantage of adaptive automation is an adjustment of workload with the goal of keeping the operator in-the-loop (Endsley et al. 1995), while avoiding cognitive overload and associated negative influences on human performance. Previous studies in varying contexts have found adaptive automation to potentially be beneficial to human performance (Parasuraman, Mouloua, & Molloy, 1996; Cosenzo et al., 2010; Calhoun, Ward, & Ruff, 2011). To test this in the context of nuclear power plants, we developed a prototype of an adaptive system to assist operators in the ramp-up of the turbine and carried out an explorative study involving control room operators from nuclear plants.

The main aspects of interest in this explorative study were a general evaluation and first impression of the adaptive automation system, its intuitiveness, the interface design, potential advantages, and disadvantages of such a system, its perceived influence on workload, other potential use cases for such a system and suggestions for improvements of the interface and underlying adaptive automation. This was done through qualitative methods, specifically observations and semi-structured interviews.

This study has been carried out as part of the thematic area "Human-automation collaboration" of the OECD NEA Halden HTO Project 2021-2023.

3.1. *Background*

The operation of a nuclear plant is highly procedural. Procedures, codifying a considerable amount of knowledge from engineers, help the operators to manage the underlying complex system. The procedures structure and plan the necessary tasks to reach a determined goal, specify how to maintain safety and to prevent damages. This is done partly by indicating preconditions which are relevant situations for guiding critical processes and indications. The application of procedures is not always straightforward and while adherence to procedures is highly recommended, not all circumstances are foreseen. This is especially true for emergency procedures (Dien, 1998) but also for normal operating procedures. In those cases, operators need to deviate from procedures to varying degrees, and for these situations a more flexible execution and better support are could significantly improve performance.

In procedures many activities could be automated, especially when new sensors and actuators are available, others require the integration of information coming from different sources, and often tasks consist of monitoring parameters against critical thresholds. Those aspects make procedures an ideal starting point to investigate possibilities for new automation. On the other side automation is not always advisable, particular conditions could require adjustments, some concurrent events could suggest alternative paths, repairing, waiting or require certain extra tasks (see also Fitts' MABA-MABA list, Fitt and Posner, 1967). This desired flexibility is the reason operators are present in the control room, continuously making sense of the situation and intervening if necessary.

Computerized procedure systems are more and more common in digitalized control rooms, giving operators support to track procedure execution. Sometimes they offer the possibility to connect directly into the procedure to perform automatic actions or check parameters. Regarding a computerized procedure system, adaptive automation offers the possibility to assign tasks beyond basic operations, by supporting monitoring of conditions and detection when moving towards critical thresholds.

The key idea in this case is to add to computerized procedures more smart, advanced automation, and exploit the procedure as the common framework where operators and automated agents cooperate to reach the goal the crew has determined to achieve.

Another aspect to consider, in addition to what automation can potentially do, is when it can do it, and how it can do it to produce the best behavior in a given situation. Traditional function allocation assigns to traditional automation tasks that can be executed in stable, fully determined, predictable conditions, and it does this at design time. As automation capabilities increase more tasks can be assigned to automation, tasks that often can be carried out by automation more effectively. Nonetheless conditions could still occur where the automation fails. With those premises a pre-determined function assignment is no longer adequate and a different strategy of human-machine cooperation, depending on the situation, must be introduced. One form of collaboration is represented by adaptive automation (Kaber et al. 2001, O'Hara & Higgins, 2020). In this context we do not adopt a specific meaning for the term adaptive automation, we look instead at the potential abilities of automation to participate in a scenario of dynamic shift in control.

The new automation can possess some relevant capabilities to play a key role in this scenario:

- Ability to gather and process huge amounts of data in real time.
- Possibility to interact with other sources of information (e.g., gathering information of

resources necessary to proceed in the procedure), integrating them and presenting to the operators at the right level of abstraction to be easily understandable. Possibility to interact with other agents, like digital twins. Possibly supporting the operators in diagnostics and problem solving.

- Possibility to follow the status of the plant and the progress of the procedure, including operator activity and workload. It could support the operator time management and planning.
- Possibility to execute activities dynamically, performing tasks on demand, interrupt its activity, roll back, restart or skip specific parts of the procedure.
- Ability to constantly interact with the operators in a suitable way, depending on the situation, providing overview, and supplying details when necessary. The ability to show its current activity at varying levels of detail, relevant goals, progress of the current activity, anomalies encountered, and similar factors.

A specific automated system can present those capabilities at different level of maturity. Those features can have a meaningful influence on human performance and, with the push towards technology adoption and market requirements to energy production, it is becoming urgent to gather insights on this impact to guide the design and development of new systems. To empirically study the impact of adaptive automation, it is possible to start with nowadays digitalized control rooms in a simulated environment and gradually introduce some advanced features. We started to investigate a form of adaptive automation for procedures, where the automation can monitor and recognize significant situations, execute independently a sequence of activities while the control over the procedure execution remains with the operator.

The introduction of adaptive automation in traditional, existing nuclear power can be disputable, for reasons of opportunity, cost-benefit balance, regulations, remaining life span of the plant and so on. More probable is the application in operation of future advanced reactors, or multi-unit facilities, like the novel Small Modular Reactors. New modes of operation and procedures will require specifically tailored automation, following the abovementioned principles. While the control of a single reactor could be simplified, the control of parallel process can introduce new challenges. Studying human automation interaction in a digitalized control room, mediated by procedures, could make it possible to abstract from the specific type of reactor.

The availability of a simulator for a Pressurized Water Reactor has allowed us to conduct a first explorative study. The results deriving from this early set up can be used as bootstrap for studies with more advanced automation and reactor types.

1.2. *Study objectives*

The objective of the study was two-fold: (1) gather user feedback on the design, functionality, usability, and user experience of the developed prototype and (2) derive operators' opinions and estimations of performance benefits of adaptive automation, which guided the development of the prototype. This was done in two rounds of studies with licensed nuclear operators from two different countries, with some adjustments being made to the prototype in between based on the feedback of the first group. Those were mainly related to usability issues of the interface.

2. Method

There were eight participants in total, partitioned in two groups. The first group was from the United States and the second one from Sweden. The two groups have different ways of structuring their work and different work cultures. The participants had different roles at the plants (shift supervisor, reactor operator or turbine operator, operator trainer) and different levels of experience. Most of them had little experience with digital systems in operation and they had mostly been working on legacy, analogue systems. The first group did receive more training on the simulator in which the prototype was integrated in. Since no performance data was collected and both groups did get the same training and instructions regarding the prototype, the effect on the findings caused by differences in simulator training was expected to be negligible.

The operators' home plants with different types of reactors were of little relevance, since the scenario was centered around the turbine system which is very similar between plants. For all participants the experimenters were available to help with questions regarding the operation of the simulator and guided the participants through parts of the operating process that was not directly relevant for the objective of the study.

The study was running single operators, so each participant went through the scenario individually. After receiving information about the study and their role, signing the consent form, and collecting demographical data, the participants were running through the first phase of the turbine ramp-up as a training and familiarization with the interface and workings of the prototype. They were encouraged to think-aloud (Charters, 2003) and describe their thoughts, actions, and expectations. Notes were taken and audio recorded during the whole session. During the second phase of the ramp-up there were two major events happening: (1) an unexpected failure of a pump that needed to be restarted by the operator manually and disabled the automated procedure and (2) a planned manual action on the generator side, for which the participants were instructed to disable the automation. After the scenario was completed, a debriefing was done including an interview focused on general evaluation, perceived usefulness, application areas, possible improvements, the behavior of the automation and limitations and shortcomings of the prototype.

2.1. *Test Environment and Prototype*

The study has been conducted at the IFE (Institute for Energy Technology) labs. The single operator setup for the study required a workstation where the operator could carry out the required tasks.

The system at the core of the study, in the following called AAProc (Adaptive Automation for Procedure), is a prototype and currently partially integrated in the control room model available at HAMMLAB (the main lab for studying human machine interaction, IFE, 2020) and integrated on the same platform, Procsee (a software tool for developing graphic interface, IFE, 2019). The whole software for monitoring the plant was available at the workstation, the essential difference with the HAMMLAB setup is the number of workstations, screens, and the absence of a large display for shared overview of the main parameters of the plant. The prototype was integrated with a full scope simulator of a generalized Pressurized Water Reactor.

For logistical reasons the setup varied slightly for the two groups of participants. With the first group of operators, at the workstation the operator had in front of them four screens, in 2x2 matrix, as shown in Fig. 1.

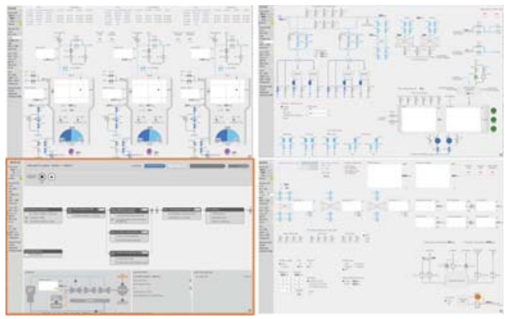

Fig. 1. Displays presented to the operators. Starting from bottom left and going clockwise: the fixed display for the AAProc, the overview and controls for the steam generators, the Main Steam System and the Turbine Control panel. In all displays, the pane on the left is used to select and bring up different control displays, allowing the operator to freely configure his/her dashboard. This functionality was disabled in the AAProc display.

In the second group the operator had in front three screens arranged horizontally. This did not appear to change the way of operating, since with the first crew we observed that no more than two of the other screens were used.

The AAProc consists of the user interface and the underlying engine. The engine is a basic form of adaptive automation interacting with the simulator to monitor conditions and actuate simple operations as indicated by the procedure. The operator can configure at any moment which steps the automation is in charge of. The second group of operators was presented with a slightly different version, which already incorporated feedback on mainly usability issues from the first group. Additionally, the new version had increased flexibility in re-starting the automation.

This first prototype represented only one initial step in the direction of adaptive automation, limited to technology readily available at our lab. At the present it uses only direct plant data, which are parameters supplied by the simulator, does not interact with other sources of information or systems, nor has it learning capabilities. The adaptiveness of the system is related to its ability to execute arbitrary parts of procedures when instructed by the operator, to synchronize automatically with operator activity and monitor extra conditions relevant for the procedure like certain stop and secondary conditions. It has a user-interface intended to give a high level of transparency of automation activity, showing what has been done, warnings and deviations, next scheduled activities, and assignments. When a deviation is encountered the prototype suspends the execution of its tasks - not the monitoring - and warns the operator. The operator can change the assignment of tasks if necessary and restart the automation when he or she considers it appropriate. The adaptiveness of this automation is solely relying on task-based events and will not increase the level of automation without being prompted by the operator, only decrease. This was deemed more appropriate in the context of nuclear power plant operation and was included in the evaluation. This first implementation helps to keep the system more understandable by the operators, it is close to realistic application in the near future and simplifies the study of the impact that otherwise could be too difficult if more features were included at the same time.

Realizing a complete automatic adaptative system, able to decide what is necessary to do in a situation, reassign tasks to human or automation, and restart automatically its own activity, means to provide the system with a larger scope, more information and knowledge. It is anyway necessary to evaluate if such level of automation is beneficial. Rather, we believe, it is more acceptable to place several checkpoints throughout the procedure where the operator can make the final decision, seeing the automation acting as support system rather than a decision maker.

Among the more relevant parameters to provide to the automation is the workload of operators. How the automation can become aware of the workload of operators remains a difficult question and there could be different approaches to tackle this (Durkee et al., 2013; Heard, Harriott & Adams, 2018). Any solution provided must be reliable, respect operator privacy, be non-intrusive and at the same time transparent, visible to the operators, the operators should be able to give feedback to it and deactivate it. An example could be a module analyzing in real time the logs of operator activity on the I&C or deducing a certain level of workflow from the alarm flow and the active procedures. This topic deserves further research.

Additional features can be gradually introduced to the prototype with modules simulating environmental conditions, sources of information and support systems. Today the prototype AAProc is tailored for the turbine rump up procedure from 520 rpm to 1800 rpm and subsequent connection to the grid.

2.2. Scenario

The scenario used to collect feedback about the system is based on the procedure for turbine rump up relevant to the simulator. The procedure can be divided in four group of actions, here called sequences, with increasing thresholds of rpms as dividing criterion. To limit the scenario run time, the starting condition assumes the first sequence already executed and the turbine sitting at 520 rpm.

Fig. 2 The main sequence of the procedure as presented in the user interface. The colors indicate the state of execution, sequence 2 is shown to be the active sequence.

To get a first impression the operators were not given formal prior training on the AAProc system, instead sequence 2 was used as familiarization with the system and this version of the procedure. Sequence 2 was supposed to be executed all in automatic, so the operator could assign the steps to the automation and then start the execution. Sequence 2 was running as expected without unforeseen events, alarms not relevant for the procedure could appear and be acknowledged in the alarm panel. At the end of each sequence the automation would stop, warning the operator of reaching this check point and waiting for operator action.

Before starting sequence 3, the operator was informed that maintenance was occurring at the generator site.

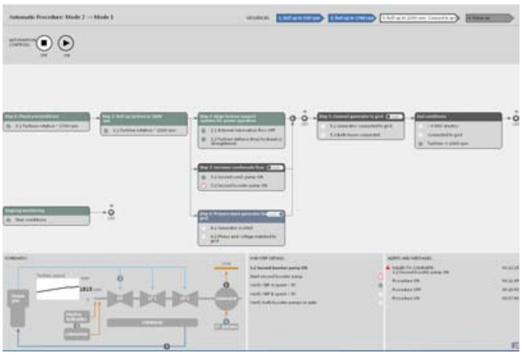

Fig. 3 Scenario, anomaly at Step 3. The automation stops while performing the activity for sub-step 3.2 after attempting to start the second booster pump and verifying that the speed of it was insufficient (the anomaly was due to a valve that was shut and needed to be opened manually).

This information led to the need to execute step 4 in manual mode. This step involves operations on the generator. The remaining steps could be left to automation, while the operator could concentrate on step 4. Step 2, 3 and 4 could be performed in parallel. During step 3, supposed to be assigned to automation, the automation recognized that the pump is not ON as expected. Then it disengaged and warned the operator about the failure. The operator was expected to manually fix the problem, as the problem was fixed and the pump running, the automation could proceed to the end of step 3. In the meantime, the announced maintenance activity had terminated and step 4, if not completed yet, could be completed by the automation. As all the parallel steps were completed, there was another predetermined checkpoint in the procedure, the automation stopped to synchronize with the operator before entering the step for connecting to the grid. The scenario ended at this point and the participants were informed by the researcher about that.

3. Findings

The feedback from the operators was generally positive and user acceptance high. All of them, coming from traditional analogue plants, with a limited level of digitalization, would welcome more automation, especially for more repetitive, low-level tasks.

At the start the operators got acquainted with the system and were following its actions by reading the procedure on paper (short version), a few (2 out of 8) having a look at the preconditions and warning described in the long version of the paper. The first approach with automation was, for everybody, to follow the effects of its actions on the plant and then comparing the behavior of the parameters displayed on the mimic/schematic with the one expected. Reliability remains a basic component of trust in automation, even when elements of intelligence are introduced in the system (Glikson, Wolley 2022). As discovering that the automation was following the procedure correctly and as they learned that details of sub steps were easy to follow on the screen, the paper version was abandoned by all the participants eventually, only to come back in a few cases for performing the manual actions required by the scenario.

Almost all operators (7 out of 8) commented about a clear potential for more efficient execution of procedures compared to the paper-based version they were used to. The ability to monitor significant conditions and stop when a problem came up was unanimously appreciated.

Regarding general concept of adaptive automation, we have seen that the possibility to flexibly assign tasks to the automation, is very well received. Thus, balancing workload as well and giving them for example the possibility to deal with some aspects in more detail or prepare for some activities when needed, while the automation operated in normal, low risk conditions.

Regarding the question if they would like the automation to take more initiative on restarting its assigned activity after a stop, unanimously the answer was "no". They see the collaboration with automation as a form of supervisory control. This answer could be motivated by the limited capabilities of the automation. In the prototype the user interaction has been designed to be compatible with this perspective, probably this factor contributes to the expressed high acceptance.

The AAProc system is viewed as an important tool for gaining a better overview of the procedure progress and its effects on the plant. All operators found the interface simple and intuitive. Through it they could understand what the automation was doing. The information presented was all in all considered sufficient, given that the system was used in combination with the other displays. Nonetheless some improvements were suggested. The most common suggestions were better indication of desired and planned actions of the operator; better information on key parameters and critical thresholds, varying with the steps; on warning of detected anomalies a more direct link to the relevant area in the operating interface. While the paper version of the procedure was not considered necessary for carrying out the task, a digital version of it, including direct links in the interface, would be useful.

The use of other screens (Fig. 1) was varying, depending on the experience and role of the operators, in general operators more familiar with the task and type of plant navigated more comfortably in the other displays, nonetheless it was noticed by some that the AAProc display was a suitable source of information for most relevant parameters, helping to reduce the navigational tasks. Normally only one or at most two of the additional screens were used during this scenario, this could be related to the task requirements.

On the question about which tasks could benefit most from a similar system and if there could be associated risks, the answer can be summarized as follows. Nobody excluded areas for potential application, in general underlining that when anomalies are present, they want to have full control over the situation, (with less possible interfering activities going on, since the main goal is to understand and come to a solution as soon as possible). Advanced automation is mainly seen as offering better support. In general, the factors in favor of usefulness and safety of application of adaptive automation are, the characteristics of the automation and possible cooperation strategies. Adaptive automation is seen positively, but the control should remain with the operator (supervisory control). Operators did unanimously prefer the automation not to take control without being instructed to, supporting our hypothesis. A frequent synchronization with the operator's activity helps to keep the operator in the loop.

We expected to hear some comment on reduction of workload, at least for some situations, instead the operators did not put much emphasis on this aspect but rather on having a more collaborative automation could help them to concentrate on gathering a better overview of the whole system and spend more time on more complex tasks, that would require more cognitive effort.

The operators found the interface intuitively understandable and were impressed by how fast they were able to make sense of it and follow the automated process. They did however on occasion miss some indications and information included in the display, for example the included stop conditions were not obvious for most of them in the first version of the prototype. When going through this in the debrief though, the majority's opinion was that with proper training and guidance of the workings of the interface of the system they would feel very comfortable to use it. Some (3 out of 8) expressed some concerns regarding automation complacency and pointed towards that as a possible risk factor.

4. Conclusion

Acknowledging that progress in technology brings new opportunities to improve the concept of operations in a nuclear power plant we started to explore the impact of introduction of advanced automation. Automation must always be introduced taking care of the processes it affects. To take care of the production process we started to exploit the knowledge operationalized in the procedures, computerize them and adding more automation. Since effectiveness of automation depends on the right combination of its capabilities, the characteristics of the task and the situation, a form of adaptive automation could be a prerequisite in future systems for high effectiveness.

We wanted to evaluate different dimension of the impact of our specific adaptive automation prototype like acceptability, usability, usefulness, potential effects on workload and awareness. The first study aimed at collecting feedback of a prototype in a simulated environment from actual control room operators from two different countries. The qualitative study consisted of informal think-aloud technique followed by interviews.

The results until now are very promising, consistently showing high levels of acceptability and usability. Somewhat differently from what we expected regarding workload, operators gave indications that the impact could be not much on quantitative side but mainly positive on the quality of their work. They strongly agreed on how they intend to use automation and which role it should have in human automation cooperation: supervisory control.

Adaptive automation is helpful, adding a desired flexibility to operators' work. To note that the automation introduced was understandable to them and the prototype has been designed to have high automation transparency.

Future work can explore different directions. The first is to observe when adaptive automation is used in the control room by the crew, as an additional agent working with them while performing more complex procedures and scenarios. A second to observe the use of similar prototype in a control room for multi-unit plants. A third is to increase the capabilities of automation, in particular the monitored data and support given to operators. There is no defined priority at this moment in this list, the dialog with the members of the Halden HTO project, will help to assign priorities.

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