Proceedings of the 35th European Safety and Reliability & the 33rd Society for Risk Analysis Europe Conference
Edited by Eirik Bjorheim Abrahamsen, Terje Aven, Frederic Bouder, Roger Flage, Marja Ylönen

doi: 10.3850/978-981-94-3281-3_ESREL-SRA-E2025-P1394-cd

A computer-based procedure tool for SMR control room operations

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There is a growing interest in advanced technologies like small modular reactors (SMRs) to address global energy demands. Computer-based procedures (CBPs) are anticipated to play a crucial role in ensuring safe and efficient control room operations for SMRs. While CBPs have been explored in conventional nuclear power plants, limited guidance exists on their design and implementation for SMRs, especially considering the unique challenges of managing multiple reactors from a single control room. This study presents the conceptual design of the CBP tool HELP (Halden ELtronic Procedure) and shares initial insights from its application in a human factors simulator study with licensed operators. A human-centered design approach was adopted emphasizing iterative development and rapid feedback from domain experts and an interdisciplinary team. The CPB tool HELP was tested in a simulator study where licensed operators managed six SMRs from a single control room. Participants evaluated the tool's usability, and a researcher provided observations on how the operators interacted with it. The findings suggest that the chosen design direction is promising. Participants navigated procedures effectively, although transitions between SMR units require further investigation. Future work will focus on refining the design, integrating additional procedures, and testing the tool across various plant types and operator configurations. Furthermore, real-time process data into the tool is planned as an initial step toward automated procedure execution.

Keywords: nuclear safety, small modular reactors, digital procedures, design prototype, multi-unit operation, human factors

1. Introduction

The global energy landscape is shifting due to rising energy demands, a growing focus on clean power and technological advancements. The United Nations Framework Convention on Climate Change (UNFCCC, 2023) identifies nuclear power as one of the key solutions to addressing global energy challenges, which has led to increased demand for nuclear expertise. In line with these trends, interest in advanced technologies like small modular reactors (SMRs) is rapidly growing (IAEA, 2024). SMRs typically have a power capacity of up to 300 MW(e) per unit and stand out for their compact and modular design (ibid.). Despite their potential, ensuring safe and efficient SMR operation necessitates addressing human performance challenges unique to these environments (Blackett et al., 2022). The Institute for Energy Technology (IFE) plays a pivotal role in researching human performance through simulator studies in the Halden Man Machine LABoratory (HAMMLAB). Much of this research is funded by the international OECD NEA Halden, Human Technology and Organization (HTO) Project. Recently, IFE has introduced the Halden SMR simulator to study the complexities of managing multiple reactors from a single control room. As future SMR control rooms are expected to be digital, computer-based procedures (CBPs) are becoming increasingly integral into this research.

CBPs are digital procedures that guide operators through procedure steps manually while presenting them in an interactive format. They enable seamless navigation between procedures, provide context-based information, and log procedure execution details. Although previous studies have explored CBPs in conventional nuclear power plants, there remains limited guidance on designing and implementing CBPs for SMRs, particularly in multi-unit settings (Nilsen & Shin, 2011; IAEA, 2024).

Most tasks conducted in nuclear control rooms are guided by operating procedures (Nilsen & Shin, 2011; Le Blanc et al., 2015, Hurlen et. al., 2024). Traditionally, paper-based procedures (PBPs) have been used due to their ease of access, straightforward annotation, and traceability. However, PBPs have limitations, including restricted navigability and an increased risk of steps being skipped or performed out of order, which can compromise procedural accuracy (Le Blanc et al., 2015). Administrative strategies such as place-keeping help mitigate these risks but can be time-consuming and divert operator attention from primary tasks (ibid.).

The transition from PBPs to CBPs is driven by the potential to enhance procedural adherence and operational efficiency. CBPs can provide automatic place-keeping, real-time process information, and automated procedure execution (Lunde-Hanssen, 2014). Additional benefits include streamlined maintenance, integration with simulator data, version control, execution logs, and remote operation capabilities.

In the context of SMRs, CBPs may benefit from simpler and more standardized procedures compared to larger reactors. However, managing multiple SMRs simultaneously introduces new challenges, particularly in coordinating and executing procedures across several units. This increases the demand for efficient, adaptable CBP tools that support operator decision-making and workload management.

Human factors studies have identified key challenges in operating SMRs, including multi-unit confusion and the need for effective staffing strategies in control rooms (Blackett et al., 2022). Despite the potential advantages of CBPs, comprehensive guidelines for their design in SMRs remain scarce. Further research is needed to explore how CBPs can mitigate operational challenges, enhance efficiency, and improve overall control room performance (Le Blanc et al., 2015).

To help address these gaps, we have developed a procedure tool, HELP, for use in human factors simulator studies. The tool is designed to enhance understanding of critical needs related to situation awareness, usability, and overall user experience. As part of the research infrastructure, HELP provides new insights into procedure design, its integration with other Human-System Interfaces (HSIs), and its impact on control room operations.

The current study presents the conceptual design of the CBP tool HELP and shares early insights from its use in human factors simulator studies involving licensed operators. Specifically, we address the following research questions:

- How can the CBP tool be designed to support safe and effective procedure execution in SMR operations?
- What are the initial experiences and observations of licensed nuclear operators using the CBP tool in a simulator study?

The goal is to illustrate the design and application of a CBP tool and share insights with professionals working on CBPs in the nuclear and other industries.

3. Method

This section outlines the design process for developing the digital procedure tool, HELP, and describes the methodology used to gather insights from its initial application in a human factors simulator study.

3.1. *Design team*

An interdisciplinary team contributed to the design process. Even if some resources changed during the development phase, all roles were represented throughout the process: project leader, human factors researcher, interaction designer, technical developer and two domain experts being former nuclear control room operators.

3.2. *Design process*

A human-centered design approach, described in ISO 11064, Part 1 (ISO, 2000) was adopted. ISO 11064, Part 5 (ISO, 2008) provided general design guidelines applicable across displays and control rooms, while user input was used to develop more specific guidelines tailored to the procedural tool. The process emphasized iterative development and rapid feedback from domain experts and interdisciplinary team members. The process was driven by workshops and working meetings, which were crucial for electing requirements and refining the concept.

Once initial requirements and user needs were identified, the team began exploring design directions. Early sketches and design concepts were presented to stakeholders to communicate ideas effectively and gather feedback before the prototype was implemented in HAMMLAB. This iterative process ensured continuous refinement and alignment with user expectations. From October 2023 to spring 2024, the project team held regular meetings, initially focusing on defining the design challenges and providing guidance for system design. As the process progressed, the focus shifted to refining the concept details. Implementation started closer to summer 2024, with the system ready for human factors simulator studies in HAMMLAB by fall 2024.

3.3. *Equipment*

Early ideas and concepts were communicated using Microsoft PowerPoint, while Figma was used to design the low-fidelity prototype of the tool. The procedures themselves were written in Microsoft Word, as it is a user-friendly tool familiar to non-technical users. To transfer data from Word to the front-end, JSON was utilized as an intermediary format. Its lightweight structure and seamless combability with JavaScript made it ideal for processing and rendering data in the user interface.

3.4. *Simulator study and participants*

The digital procedure tool was first employed in an empirical study conducted as part of the HTO project in HAMMLAB during the fall of 2024. The study involved three-person crews consisting of licensed operators. The operators were tasked with managing six SMR units across six different scenarios. Each scenario lasted approximately 35 minutes and included both planned tasks and unexpected malfunctions affecting multiple units. At the start of the scenario, participants were typically instructed to adjust the turbine load on one or more units. The malfunctions ranged from instrument and equipment failures to events triggering safety system activation and reactor trips. The procedures were accessible via three iPads, with one allocated to each operator. Prior to the study, participants were briefed on its purpose, provided informed consent, and completed a background questionnaire. The participant group consisted of 15 men and 1 woman, with an average age of 43.5 years (SD=5.9) and an average of 7.1 years of experience (SD=5.8) as control room operators. One participant used HELP solely for single-unit scenarios (part of a separate study). Paper-based procedures were available as a back-up throughout the study.

3.5. *Usability evaluation*

Upon completing the scenarios, participants evaluated the usability of the procedure tool by filling out a paper-based self-completion questionnaire using the System Usability Scale (SUS, Brooke, 1996). The SUS scale includes ten items rated on a Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree).

To gather insights on operator interactions with the procedure tool during the simulator study, feedback was collected from the researchers who observed the participants. The insight aimed to capture the researcher's observations on how operators used the procedure tool and to identify any challenges or issues encountered during the simulations.

4. Results

The results are summarized in two parts: 1) Concept description, and 2) Early user feedback.

4.1. *Concept description*

4.1.1. *Guiding principles*

The primary goal of the digital procedure tool was to establish a foundation for CBPs in HAMMLAB simulator studies of SMRs. The tool needed to be flexible to accommodate future enhancements, including both single and multi-unit operations, allowing for the addition of new procedures, features and support for data collection and analysis. It was designed to assist operators in decision-making and ensure accurate procedure execution. Additionally, the tool should facilitate the addition and revision of procedures through an integrated editor. For multi-unit operations, each unit required its own set of procedures.

We selected a subset of principles from ISO 11064, Part 5 (ISO, 2008), to guide and focus the initial development of the interface for the procedure tool HELP within the control room environment:

- Support mental models (ibid., p. 9)
- Keep human-system interaction simple with minimal set of rules (ibid., p. 12)
- Minimize the risk of errors by assisting the operator in entering information (ibid., p. 12)
- Support the operator automatically by inputting readily available data (ibid., p. 12)
- Provide the operator with appropriate feedback at all times (ibid., p. 13).

Throughout the design process we focused on requirements specific to the procedure tool. These were informed by a combination of established usability guidelines (ISO, 2008), user involvement, and the authors' professional experience in designing intuitive systems for operational environments:

- Carefully consider the placement of important information to minimize the risk of errors and misunderstandings.
- The interface must be easy to use, with design choices that accommodate operators' varying skill levels and experience to ensure a smooth workflow.
- Maintain a consistent design style and placement of key elements to avoid confusion and facilitate learning over time.
- Ensure flexibility in the system to accommodate future development.
- Use visual elements to establish a clear hierarchy of information, aiding quick and accurate decision-making.

4.1.2. *Users and roles*

HELP was designed to support human factor researchers in conducting simulator studies involving control room operators, who served as the end-users of the tool. We needed to accommodate users ranging from experienced operators with extensive plant operation backgrounds, to students. The tool was new to all participants attending SMR studies in HAMMLAB for the first time, so it needed to be easy to learn. Primary end-users of HELP assumed to have two roles: the procedure executer (operator), who performed the steps outlined in the procedure, and the procedure supervisor (another operator or shift supervisor), who ensured the steps were followed correctly and monitors which procedures was completed at what unit. In addition, an administrator role was established, allowing for the configuration of user permissions, unit settings, and other system parameters. The identity of the logged-in user was always visible. Each operator could only edit the procedure they were currently working on (i.e., the active procedure), in addition to view (shadow) procedures that the other operator had open or active. The shift supervisor had permission to view all procedures.

4.1.3. *Unit and procedure navigation*

Upon entering the system, operators first selected the unit before choosing the type of procedure (operating, abnormal or emergency procedure). If multiple units were involved, it had to be clear which unit was selected, indicating the unit the operator currently was working on.

To ensure that operators easily could navigate between procedures and within procedures without losing overview, unit navigation was available on all pages for the multi-unit concept (Fig. 1). Additionally, the main procedure types, operating, abnormal and emergency, were always accessible via the main navigation.

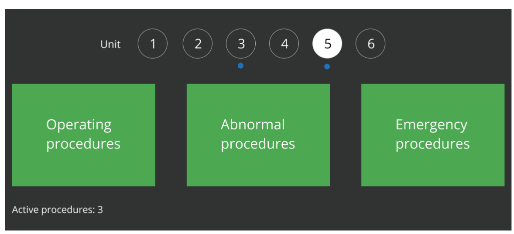

Fig. 1. Multi-unit navigation

Navigation links within or between procedures, was available and clearly indicating the procedure type through the navigation menu. Active procedures within a unit was visibly highlighted in relation to that unit. Additionally, a list of the operator's active procedures was provided for easy access.

The active unit was highlighted in white color, and a blue dot below the unit number indicated that the unit had active procedures in progress. Operators could navigate directly from one procedure to another within a procedure step. A procedure was activated by clicking the button "Activate procedure" (Fig 2).

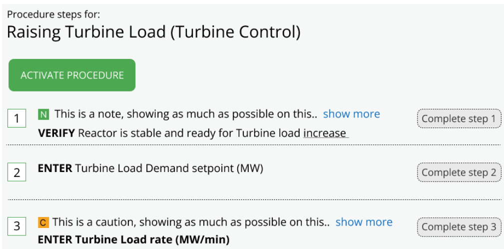

Fig. 2. Activate procedure

4.1.4. Design of user interface

The intention with the interface of HELP was to enable the operator to both look ahead at the next procedure step and review completed steps. By looking ahead, operators could anticipate upcoming actions and get a broader context for the current task. In case of an issue or anomaly, operators could also revisit previous steps to gather information for troubleshooting and diagnosis.

The procedure display emphasized the procedure steps themselves rather than navigation between different procedures. All steps within a procedure were displayed together, with indications of which steps had been completed. Steps had to be executed in sequence. A locking mechanism assigned each step to the operator and unlocked it only when it was ready for execution. Upon completion, each step was signed off with the operator's initials, date and time (Fig. 3). The interface supported operators with features such as place-keeping, notes, cautions, symptom/ conditions, and major action categories. Place-keeping helped operators stay focused on the current step, while maintaining visibility of past and future steps, providing an overview and ensured adherence to the correct path.

The procedures were presented in either a single-column or a double-column format. Operating procedures were presented in a single column (Fig. 3.), whereas abnormal and emergency procedures was shown in two columns (Fig. 4). The solution was set up responsive, ensuring a seamless user experience by adapting smoothly to both landscape and portrait orientations on the iPad. The operators used both the single-column and double-column procedures on iPads during the simulator study.

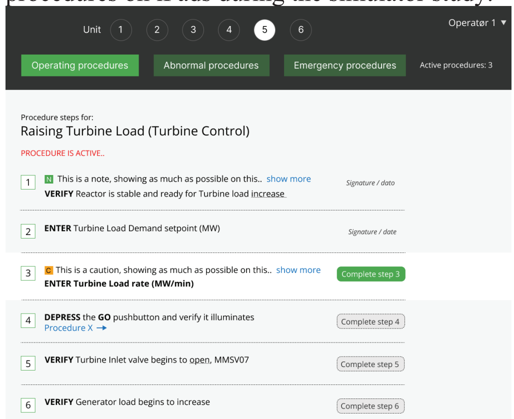

Fig. 3. Single-column procedure

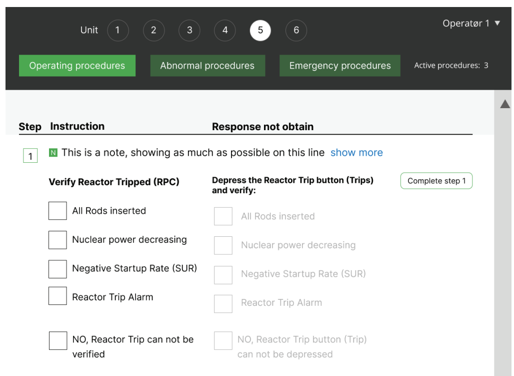

Fig. 4. Double-column procedure

4.1.5. *Process data*

The system was designed to plan for future integration of process data from the simulator (e.g., pressures, temperatures), enabling operators to determine when conditions are met for various steps.

4.2. Early user feedback

In our study, the digital procedure tool HELP achieved a mean SUS score of 80.6 (SD = 11.8). Using the Sauro-Lewis curved grading scale (2016), our score corresponds to an A-. While no direct comparisons to other computer-based procedure tools are available, benchmark data for SUS scores across various technologies indicate that scores above 80 generally reflect strong usability and user satisfaction (Bangor et al., 2009; Brook, 2013). Given the variability in SUS benchmarks across different product categories, further research is needed to establish a usability baseline specifically for CBP tools.

The researcher observed that participants quickly became proficient in using the procedure tool. Most shift supervisors effectively utilized the shadow mode to monitor the operators' ongoing tasks. Participants demonstrated ease in navigating between different procedures. However, a notable issue arose when operators transitioned between SMR units; they occasionally neglected to update the unit within the procedure tool. As a result, while they selected the correct procedure, it remained associated with the previously worked unit.

5. Discussion

This study illustrates the design of a CBP tool for operating SMRs and presents initial experiences and observations from operators using the tool in a simulator study.

The design process began by thoroughly understanding the context and defining initial expectations and user needs. We found that early-stage idea development, through sketches and concrete design, proved invaluable for aligning the project team and refining feedback during the initial phase. The user requirements outlined at the beginning of the project gradually evolved into guiding principles for the concept. These principles acted as a compass throughout the project, ensuring that initial expectations, needs, and requirements were consistently met.

Some design principles, such as a single-column view for operations and a double-column view for abnormal and emergency procedures, were directly carried over from PBPs. With more time, a deeper focus on assessing these design choices and exploring alternative solutions for presenting procedures could have yielded more optimized outcomes. Place-keeping emerged as a critical feature, designed to guide the operator through each procedure step, ensuring that no steps were missed or executed out of order. The design aimed to support both single- and multi-unit operations, depending on the configuration set by the user administrator. Observations from researchers during the simulator study, however, suggested a potential risk of unit confusion in multi-unit contexts. This aligns with challenges pointed in previous research (Blackett et. al., 2022). The extent to which HELP enhances efficiency and improves control room performance remains to be investigated. We recognize that factors such as situational awareness, usability, and the overall user experience are likely to play a significant role in shaping both efficiency and performance. With a working prototype and a group of licensed operators, we were able to gather early feedback on the system's viability. The results indicate that the direction we have taken is promising, with specific areas for further exploration. Notably, the transition between SMR units warrants additional investigation and refinement. Observations from the researchers in the study confirmed that participants were able to navigate easily between procedures. However, we still lack detailed insights into the usability of the tool during the execution of individual procedures. This gap highlights an important area for future research and improvement, ensuring that the tool supports operators effectively throughout the procedure execution process.

Our evaluation was conducted in a simulator study, a setting that closely mirrors real-world training environments for licensed nuclear operators. As part of their standard training, operators are accustomed to simulator exercises and performance observations, reducing potential biases related to observation effects. While this setting allowed us to test the tool in a highly controlled and representative environment, long-term use in real-world operational settings could reveal additional usability aspects, particularly regarding the integration of the tool into routine workflows. However, given that the tool is designed specifically for simulator-based applications, its evaluation in this context remains appropriate. Future studies could further explore how usability and operator interaction evolve over extended periods of use.

6. Conclusion and further work

We have developed and successfully implemented the digital procedure tool, HELP, which was tested during a full-scale simulator study of multi-unit SMR operations. The primary objective was to establish key design principles and assess the tool's feasibility and usability. Initial results are promising, indicating that HELP can effectively support SMR operations.

Looking ahead, several areas require further development. The next steps involve refining the design based on feedback from stakeholders and end-users, incorporating additional procedures, and testing the tool across varying numbers of SMR units and operators in the control room. Additionally, the tool will be adapted for use in a large single-unit plant simulator, where it will need to support longer and more complex procedures. Multi-unit operations present unique challenges in procedure management, particularly in scenarios where operators need to shift focus between units. These transitions, which may involve peer checking and the continuation of procedures by different operators, require in-depth exploration to ensure seamless operation and coordination. As future plants are expected to be highly automated, an important direction for HELP is the integration of real-time process data from the simulator into the procedure. This enhancement could automate certain steps and sequences, such as verifying conditions and performing continuous monitoring, leading to a more efficient and automated procedure management system.

Acknowledgement

We thank the technical team; Daniel Odéen, Håkon Jokstad, Tom-Robert Bryntesen, Terje Bodal and Aleksander Lygren Toppe, for their invaluable contributions. Their insights and efforts were instrumental in the development of the procedure tool.

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