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Future needs of human reliability analysis: The interaction between new technology, crew roles and performance

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ABSTRACT

Human Reliability Analysis (HRA) is an important part of probabilistic risk/safety assessment (PRA/PSA) for nuclear power plants (NPPs). Data has played a central part in HRA, to underpin nominal task probabilities, providing time reliability estimates, and as a basis for multipliers for performance shaping factors (PSFs). New NPPs apply digital instrumentation & control (I&C) systems to support monitoring and control. Will this require new or updated HRA methods and more data as compared to today? We have seen that the combination of the new I&C technology and how it is used by the crew is decisive for the performance of the joint system, comprising the crew and the I&C technology. This paper focuses on the way in which new technology may affect human performance as well as the relation between crew roles, teamwork, and performance. For HRA, two questions are important: What is the impact of teamwork and assigned crew roles on recovery from failure and upset plant conditions? And how should dependency be treated in modern control rooms? This paper discusses these matters based on empirical studies in the OECD Halden Reactor Project and underlines the importance of empirical studies on these topics, since the interactions between new technology, prescribed work processes and actual practices, and crew behavior, are often not obvious. This paper is an extension of a paper presented at the ESREL 2020 – PSAM15 conference.

1. Introduction

New technology, unless underlying a fully autonomous system, cannot be evaluated stand-alone. It is important to evaluate how it impacts the performance of the joint human-technology system, as human interaction with the system is inevitable. In this, one aspect often forgotten is the way in which the new technology affects both teamwork and assigned roles in the plant operating crew. The other message in this paper is that it is important to study these topics empirically, since it can be very difficult to imagine many of the observed phenomena beforehand.

1.1. Current treatment of teamwork and crew roles in HRA

HRA analyses the human contribution to risk, especially as evaluated in Probabilistic Risk/Safety Assessment (PRA/PSA). This is established practice within the nuclear power plant industry. What is the historical treatment of crew roles and teamwork in HRA? The first recognized HRA method is A Technique for Human Error Rate Prediction (THERP) by Swain and Guttman (1983). Already in that method, they considered "Team Structures" (ibid., p. 3–28) as a part of "Task and Equipment Characteristics" that should be evaluated in an analysis. The consideration of teams was especially linked to error recovery factors, such as "Checking Operation" (ibid., p. 19–4). Interestingly, recovery and teamwork are still among the open issues that are not finally settled, as we shall see in this paper.

Many other HRA methods have also included teamwork in some way as a PSF. In 2005, the U.S. Nuclear Regulatory Commission (NRC) issued a method-independent guidance document "Good Practices for Implementing Human Reliability Analysis" (Kolaczkowski et al., 2005). Here they recommend the PSF "Team/Crew Dynamics and Crew Characteristics [Degree of Independence Among Individuals, Operator Attitudes/Biases/Rules, Use of Status Checks, Approach for Implementing Procedures (e.g., Aggressive Crew vs Slow/Methodical Crew)]". Most of the HRA methods out there today incorporates teamwork as a PSF in some way.

The newest HRA method from the U.S. NRC is Integrated Human Event Analysis System for Event and Condition Assessment (IDHEAS-ECA) (Xing et al., 2020). IDHEAS-ECA models critical tasks "using five macrocognitive functions: detection, understanding, decisionmaking,

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action execution, and interteam coordination" (ibid., p. v). Failure of any of these functions is called a Cognitive Failure Mode (CFM). In addition to interteam coordination modeled explicitly as a CFM, teamwork is treated in two performance influencing factors (PIFs, similar to PSFs): "Teamwork and organizational factors" and "Work processes". These two PIFs can influence all the other CFMs for each task. The former deals with team communication, coordination and cooperation, while the latter includes e.g. supervision and management support (ibid., p. 2–5).

1.2. Current use of data for HRA

Kolaczkowski et al. (2005, p. 5-12) noted the importance of empirical grounding of the knowledge used to analyze the "Team/Crew Dynamics and Crew Characteristics" factor: "Note: Observation of simulator exercises and discussions with operating crews and trainers are particularly important to obtaining this type of information. Weaknesses and strengths in organizational attitudes and rules as well as in administrative guidance may bear on aspects of crew behavior and should be considered." This note emphasizes the importance of knowledge of these crew matters at the specific plant for which the analysis is done. I would also argue that the acquisition of such empirical knowledge can be prepared for in a better way if analysts can read and/or genuinely see the variety of empirical results on these very same topics e.g., from simulator studies. This enables analysts to know what to look for and to know which questions to ask.

Boring (2012) gave a thorough description of the historical development of THERP and by that also HRA in general. He describes the use of data underpinning THERP. The role of data, mainly quantitative data, for HRA was also described in (Bye, 2018):

to underpin basic task probabilities, based on data for nominal behaviors.

to provide time reliability estimates for diagnosis assessments.

to estimate multipliers for PSFs. Based on an analysis of the context, these PSFs are then used to adjust the nominal task probabilities.

IDHEAS-ECA (Xing et al., 2020) utilizes data according to the first and last bullet points above. There are three base PIFs that provide base human error probabilities (HEPs) for each of the five macrocognitive functions (corresponding to the CFMs). In an analysis, the other PIFs can modify this base HEP with the use of multipliers. All of these base HEPs and multipliers are deduced based on empirical data.

In a more general form of knowledge, qualitative data can also be used to support consistent use of the HRA methods, e.g., making anchor points for assumptions in the guidance. In a field in which expert judgement has been and will be important, qualitative data is important for understanding the nature of human operation, for example when and why errors occur. Such knowledge can support consistent use of HRA methods, thus reducing inter-analyst variability in quantitative estimates. IDHEAS-ECA has also utilized this kind of data usage, by providing a set of "PIF attributes" for each PIF, describing typical anchoring conditions for the PIF with corresponding values, see the tables in Appendix B (Xing et al., 2020, pp. B-1 – B-23). The anchor points are an integrated part of the method with separate values based on specific descriptions. Other methods often use more general descriptions in guidance documents in order to obtain a consistent use of the method. Such general guidance is more prone to variability in the basic knowledge of the analyst.

There are several recent activities that addresses the use of data from various sources to support HRA in general, see Bye et al. (2019). The U.S. NRC has undertaken a large data collection effort in their Scenario Authoring, Characterization, and Debriefing Application (SACADA) project (Chang et al., 2014). This is a joint effort with training departments at nuclear power plants, in which instructors collect data for HRA from training sessions. These data have been used in the IDHEAS-ECA method, and SACADA is also providing the data basis for other newly developed methods, such as Phoenix (Ekanem et al., 2016).

Human Reliability data EXtraction (HuREX) (Jung et al., 2020) is another example of a data collection framework to support HRA. An HRA method for digital main control rooms was then developed, EMpirical data-Based crew Reliability Assessment and Cognitive Error analysis (EMBRACE) (Kim et al., 2019), (Kim et al., 2020). EMBRACE is based on the same structure as HuREX and utilizes the data directly in the method.

A classic method based on data is Nuclear Action Reliability Assessment (NARA) (Kirwan et al., 2004). There is a growing interest in understanding whether the underlying data for existing HRA methods support analysis of modern control rooms (Bye et al., 2019).

Electric Power Research Institute (EPRI), IFE, Idaho National Lab (INL) and Korea Atomic Energy Research Institute (KAERI) have a collaborative work (Presley et al., 2021) to suggest a template to integrate research results obtained from diverse studies, to be able to support many HRA methods with detailed empirical data. In an approach for better sharing of empirical data and results from human performance studies, the Halden Project has proposed a human performance repository (Bisio and Massaiu, 2020).

Data has also been used as a basis to evaluate HRA methods, such as in the International and U.S. HRA empirical studies (Bye, 2018; Forester et al., 2014; Forester et al., 2016; Liao et al., 2019). Also, data can be used to answer and resolve basic questions, such as comparing digital and analog human-system interfaces (HSIs) enabling and supporting the performance of basic tasks, e.g., detection tasks (Bye, 2018).

For the new challenges arising with new digital control rooms and their interaction with teamwork and crew roles, as Kolaczkowski et al. (2005) points out, data will also play an important role in the evaluation of this team and crew dynamics. Note that they name this "crew dynamics", it is not a static factor. This paper describes new empirical knowledge gained in the Halden Project on the relation between digital HSIs in the control room, crew roles and teamwork.

It is also interesting to note that Xing et al. (2020) note that the factors teamwork and work processes and their direct impact on human reliability still lacks empirical data (ibid., p. 4–3).

2. Future challenges in NPPs

The nuclear industry is modernizing the fleet of plants, and at the same time, the requirements for safety are as strict as ever and demands for safety assessments expand into new areas. The nuclear industry has required analyses of areas such as PRA for flooding and fire. Recently, this has been expanded to modelling extra installed equipment and the response of human operators in severe accident conditions. These situations are characterized by higher uncertainty for the operators, especially regarding which indicators they can trust to show correct values, and which safety systems they know they can rely on. Thus, operator decision making in these unforeseen situations is challenging. The procedures might not support the operating crew in these situations (Massaiu and Holmgren, 2014). This also creates a challenge for HRA analysts. The analysis of errors of commission (EOC) requires the use of additional methods of analysis. In the not so far future, one may also envision that cyber security threats will become more imminent. This will even further expand the scope of analysis for within and beyond design basis accidents and incidents.

As long as humans are involved in the operations of the nuclear plants, we need to analyze the safety implications of human decision making, planning and action in NPP accident and incident scenarios.

2.1. Modern control rooms, digital I&C

New NPPs contain digital Instrumentation & Control (I&C) systems. Will this require new or updated HRA methods as compared to today? If so, we will need data to inform the HRA methods.

Some tasks remain the same regardless of whether the control room is analog or digital. New challenges in modern control rooms include differences in basic interaction tasks between analog and digital systems. These topics are studied in various projects, and micro-task methodology is one example that may be used to study this (Hildebrandt and Fernandes, 2016). Applying the micro-task methodology, one can assess and compare the performance of basic low-level tasks like (alarm) detection in an analog and a digital control room. Other new features that can be advantageous or rather challenging for control room crews in modern control rooms are computerized procedures and higher levels of automation (Choi et al., 2018).

New technology is intended and expected to give the operators a better and simpler platform to perform their work. This is one of the drivers to upgrade and modernize systems. However, there are also other drivers, such as lack of spare parts, modernization of other parts of the plant and that the technology in the control room must be upgraded as an add-on to the other upgrade. In some cases, it might be so that the work for the operators get more complex, especially adding on more navigation tasks in the interface. (O'Hara et al., 2002) and Zou et al. (2017) showed that more interface management tasks lead to higher cognitive and working loads. This again can lead to higher HEPs and reduced situation awareness (SA). O'Hara et al. (2010) conclude that "I&C degradations are prevalent in plants employing digital systems" and that "deterioration of the sensors can complicate the operators' interpretation of displays". Thus, there is a chance that new systems create more complexity for the operators.

The impact of lack of indicators was also studied by Nystad et al. (2019). They found that misleading (incorrect) indicators were more difficult to handle for the crews than missing indicators. This was especially evident in the operators' trust in the HSI (Kaarstad and Nystad, 2019).

3. The link between new Technology, crew roles and performance

The way in which the control room crew works together is important for the performance of the joint system. The intended and expected practice of crew collaboration is typically specified in the Conduct of Operations, in which the crew roles, the work processes and the training is outlined. This is still important with new technology, since the new technology gives many flexible opportunities for implementation, and there is less experience over years in how to work as a team with the new technology. To which extent will the crew roles and teamwork change in a modern control room?

3.1. Complexity and teamwork

In an empirical study in the Halden huMan Machine Laboratory (HAMMLAB) with licensed NPP operators, Braarud and Johansson (2010) studied the relation between task complexity and teamwork. Team cognition was studied in five dimensions: "Mission analysis - Cognition beyond procedure guidance; Process of consultation while performing technical work; Distributed leadership (mainly between Supervisor and Reactor operator); Team orientation; Backup and support". The conclusion was that the more complex the tasks get, the more does (bad) teamwork impact performance. Two cases were designed and tested: a base type scenario with few additional difficulties for the crews, and a complex variant of the scenarios. These exact scenario runs were later re-used in the International HRA Empirical Study (Forester et al., 2014), since the manipulation in a base and complex variant was spot-on for HRA method testing. In the base variant there was no correlation between team cognition rating and diagnosis time, meaning that the crew diagnosed the situation as fast independent of the quality of their teamwork. In the complex case, the diagnosis time went considerably up when the quality of the team cognition was bad. See Fig. 1 and Fig. 2.

The extended time for diagnosis in the complex case could be seen in that the crews had difficulties interpreting and following the procedures, since there was a mismatch between procedures and the plant situation. The procedure following issues in these scenarios are described in detail by Massaiu and Holmgren (2014). They showed that due to the complexity made by the lack of certain indications that the procedures asked for, many different paths through the procedures were observed, and these led to the extended diagnosis time. In Fig. 3 the various procedure progression paths are shown in typical condition, meaning the base-case scenario, and in non-typical conditions, the complex scenario (Massaiu, 2018). The underlying data is described by Lois et al. (2009, Table 2–8, p. 2–20).

There are a number of reasons for these diverse procedure paths,

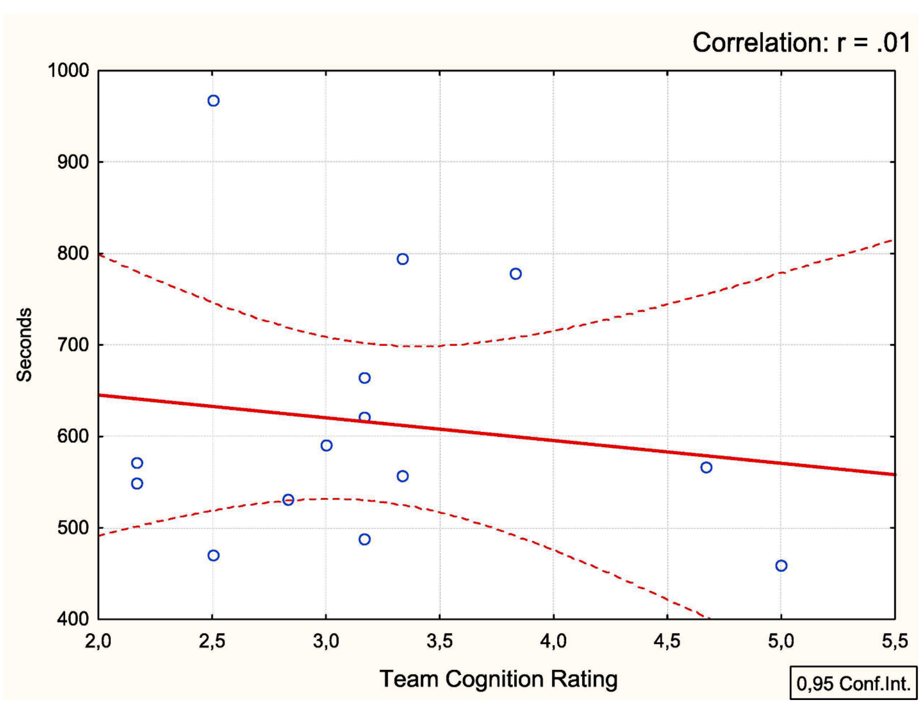

Fig. 1. Base case scenario. Team cognition quality less influential on diagnosis time. From (Braarud&Johansson, 2010, Fig. 2, p. 38).

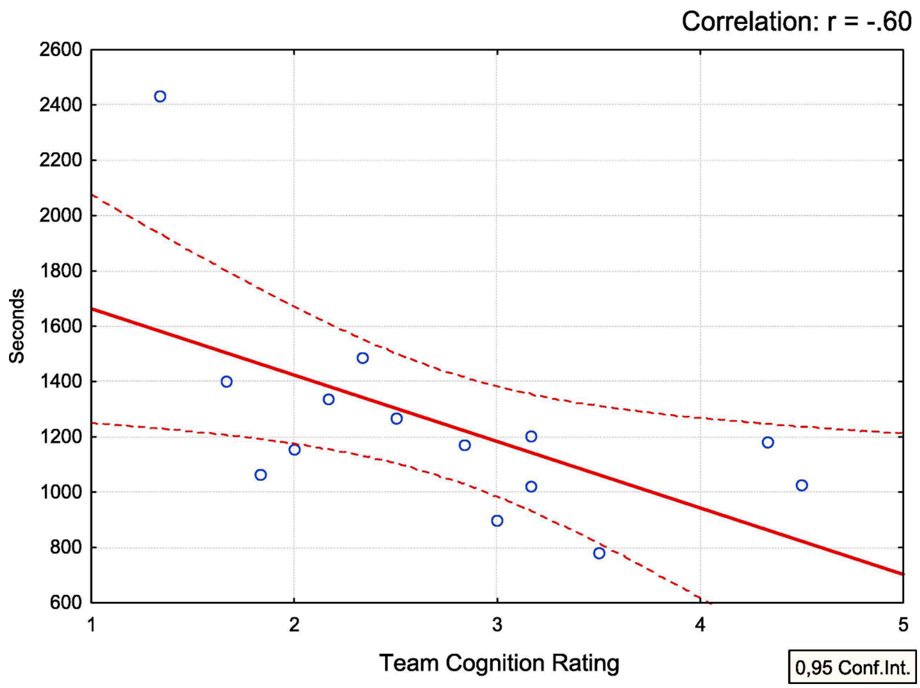

Fig. 2. Complex case scenario. Team cognition quality more influential on diagnosis time. From (Braarud&Johansson, 2010, Fig. 3, p. 39).

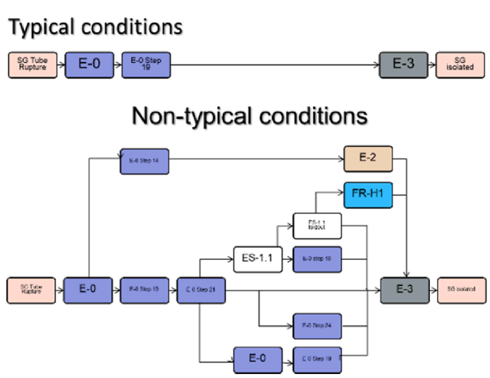

Fig. 3. The difference in procedure paths of various crews in the baseline scenario (Typical conditions) and the complex scenario (Non-typical conditions). From Massaiu (2018).

including challenges in procedure following due to timing issues in the scenarios. Massaiu and Holmgren (2014) discuss these challenges and resulting conclusions in detail.

This link between complexity and teamwork is important to have in mind for new plants as well. If the new system creates more complexity and more workload for the operators, it is even more important to establish good teamwork in the crew.

3.2. Computerized procedures and how they are executed and followed by the crew

New computerized procedure systems (CPS) may evaluate plant conditions automatically. This is a feature that may be implemented to support the crew in progressing effectively through procedures. However, what happens if the automatic evaluation function fails? Should this be considered when designing the automated system and how the crew would collaborate with the automated system?

In order to test whether participants would detect a failure in the automatic evaluation function of the computerized procedure system, a small-scale study was performed at an instructor facility simulator, see Taylor et al. (2017). The main finding was that "false positives" (an erroneous green checkmark, indicating that the required parameter was met, when in fact it was not met) of the computerized procedure system was not detected by the test subjects, while "false negatives" (erroneous red cross checkmark, indicating that the required parameter was not met, when in fact it was) were detected. This might indicate that the opportunity for false positives might be a problem in the interaction between operators and computerized procedures. False positives is a general issue addressed in many fields.

The primary limitation of the study was the sample size and the ecological validity, since the crew consisted of three instructors (i.e. not licensed operators). In later observations at a real plant with a similar type of system, similar behavior was not observed (Hildebrandt and McDonald, 2020). The crews were highly trained to follow the conduct of operations stating that all automatic checking in the procedure system should also be checked manually. Thus, this type of behavior and the error mechanism is dependent on a number of factors, including the conduct of operations, and how strictly the conduct of operations are trained and enforced, the way in which the information is presented, the transparency of the system, and its reliability. Training is a very important factor that can compensate for suboptimal design of human-system interfaces and human–computer interaction. This study was an observation study in typical baseline conditions. So, it remains unknown how crews will behave in situations where the time pressure is much higher than normal, in a 'live' environment, in which human performance is affected by e.g., workload. This issue becomes even more critical since in many modern control rooms, the reactor operator reads and executes the procedures, thus potentially leading to high workload in some situations. On the other hand, it should be considered that in such organizations the supervisor often has relatively less workload compared to an analog control room, in which normally the conduct of operations requires the supervisor to read each procedure step loud to instruct and brief the reactor and turbine operators to execute the actions. So if the supervisor does not have to direct the procedure execution, this will free up attentional resources for oversight, which may increase the ability to detect errors. From an HRA perspective the analyst should consider whether automatic systems are dominated by positive feedback, and to evaluate how checking of automatic feedback is trained.

KAERI has investigated the effects of operators' work style with CPSs on workload. Kim et al. (2014) studied three types of activities, cognitive; communicative; and operative activities, for the different operating crew members in performing emergency operating procedures through a CPS. They found that (ibid., p. 749) "the SSs [Shift Supervisors] had a larger amount of workload than the BOs [Board Operators]. In particular, the SSs showed a large amount of workload for following the procedures." This was mainly due to an increase in operative activities, in which 88 % consisted of clicking buttons for confirming that steps or sub-steps had been carried out. So, the shift supervisor was in practice "shadowing" the procedure. Thus, they conclude (ibid., p. 750) "the SSs conducted more activities than other operator roles, and the CBP [Computer Based Procedure] requires the SSs to conduct lots of operative activities.".

In a follow-up study, Kim et al. (2016) tested different strategies to mitigate the imbalance in workload distribution within the crew. They tested two different delegation strategies when working with the EOPs, and concluded that (ibid., p. 1110) "the workloads between operators in a control room can be balanced according to the operations strategies by assigning control authority to the operators. In other words, the suggested operations strategy was found to mitigate the imbalance".

By this we can conclude that there is a strong link between the implementation of a computerized procedure system and the work style of the crew, and that this relation can have a big impact on the workload of the operators. It is also clear that the distribution of the workload can be adapted by introducing new operation strategies.

There are also other interesting challenges in the use of CBPs. Examples are the effects on performance by following various strategies such as reader-doer strategies when performing EOPs. Variants of the operations strategies that were tested by KAERI are interesting, e.g., any difference in performance of the classical "shift supervisor reads, reactor operator executes" vs "reactor operator reads and executes" the procedure. The former strategy is typically followed in a traditional analog nuclear control room, while the latter is at least enabled in new digital control rooms. In the same study as mentioned above, Hildebrandt and McDonald (2020) did some observations of the latter in a digital control room. A preliminary conclusion was that the communication, including three-way communication, went considerably down (40 %) compared to a reader-doer process (Hildebrandt and McDonald, 2020). Thus, the execution time of the procedures went down making the procedure execution more effective. No negative performance effects were observed in this study. However, we don't know whether less communication is good or bad in the long-term.

As in the cases reported by Kim et al. (2014 and 2016), this result shows that there is great amount of variability and configurability of how crews interact and work with procedures. Various solutions should be studied in more detail in order to conclude on performance effects and derive optimal solutions.

4. Role independence

In the former section, we saw evidence that the interaction between new technology and the work style of the crew impacts performance. However, there are many examples that work style and teamwork affect performance in themselves. Aspects of this that Halden is studying now, are independence between roles in a crew, grouping and positioning in the control room.

4.1. Positioning of crew members

In a study carried out in HAMMLAB in 2010, Strand, Kaarstad, Svengren, Karlsson and Nihlwing (2010) explored team transparency (Strand et al., 2012). It has been suspected that in a control room equipped with digital HSIs, the crew members may have less overview of their colleagues' activities and whereabouts than in analog control rooms, where conventional panels are the means of operator interaction with the plant. The simple background is that in an analog control room the physical position of an operator, e.g., in front of the safety panel, implies that he/she is working on that panel. In a digital control room, all the operators normally stay put on their desk regardless which system they are operating. Strand et al. investigated various digital solutions that were supposed to improve team transparency in a digital control room. One example was frames around equipment in the displays of the shift supervisor, indicating which system the operators were working on. Although the Shift Supervisors were positive and felt that they could more easily follow the reactor operator and turbine operator's work, no performance effects of the proposed solutions were identified (Strand et al., 2010). The first three crews participating in this study tended to gather in front of one workstation. This was not good in a study on team transparency, so the next six crews were instructed to work from their respective workstations. These crews were the ones that were used in the analysis of the original study. In a re-analysis including all the crews, Skraaning (2016) found that the crews that were positioned at their respective workstations performed significantly better than the crews that grouped together. Skraaning notes that (ibid., p. 20) "this was an explorative reanalysis of a study designed for another purpose, and not a controlled experiment. The findings are therefore inconclusive and should be replicated before they are used to promote nuclear safety.".

Kaarstad (2019) has described this story and discussed the findings related to known teamwork effects in order to understand more about why there were performance differences between the two groups. Was it an effect of groupthink, poor task delegation or other teamwork effects? Kaarstad (2019) and Kaarstad and Nystad (2020) investigated this in more depth by interviewing operators and studying videos from the experiment. Topics like groupthink and authority in teams were explored. This is a thorough basis for future studies, and several interesting questions to be studied arise:

- To which extent is work style impacted by the digital control room? Does a more compact control room "invite" people to closer group work?
- How does communication change based on the layout and style of the control room? If communication is affected, how does this impact situation awareness of the crew?

4.2. Independence of the shift technical advisor (STA)

In a study on "Resilient procedure use" (Massaiu and Holmgren, 2017), the effects of supporting tools in the form of a shared overview display and a computerized procedure flowchart tool, as well as a supporting role of a Shift Technical Advisor (STA) was studied in demanding emergency scenarios. Massaiu and Holmgren (2017) concluded: "While the statistical analysis does not show significant effects of the manipulations, the qualitative analysis observes positive effects in given circumstances. The extra operators and the procedure system had positive impacts when the STAs were knowledgeable and experienced; when they divided their duties efficiently with the crews; and when the other operators needed support.".

The results regarding the STA were especially intriguing. Asking why the STA did not improve general performance of the crew, plausible reasons were that the STA was working as a team member, getting involved in the crew's work, and being delegated tasks from the Shift Supervisor. This might be similar effects as were found in the analysis described by Skraaning (2016) in section 4.1. Anyways, the conclusion was that the STA did not function as an independent advisor.

After the Three Mile Island accident (Kemeny, October 1979), the Shift Technical Advisor (STA) role was introduced in U.S. NPPs, as described e.g., in NUREG-0737 (1980). This role was from the U.S. NRC's side meant to provide additional technical and engineering expertise and should report to the shift supervisor during off-normal plant conditions in an advisory capacity. When the plants have implemented the STA role, many of them have focused on the independence of the STA from the rest of the crew (R. McDonald, personal communication, February 2020): "The design at all the plants is the STA should remain independent from the crew's action and provide an oversight and verification that the crew is progressing properly as well as looking ahead in the procedure." R. McDonald (ibid.) continues: "What I have seen today is that most sites have the STA as a crew member, backing up the Emergency Plan call by the Shift Manager, and getting the procedures out for the Control Room Supervisor (CRS), and even having discussion with the board operators. So their independence has been compromised in that they now are more crew members than outside observers. It doesn't help that many plants use the CRS and STA as interchangeable roles (the STA is also a licensed SRO-Senior Reactor Operator) so that can make distinguishing the person for the role difficult." This is the same observation as in the study described above.

In order to study this in more detail, Kaarstad and Nystad (2020) initiated a new study. In-depth qualitative analyses of the transcriptions of the "Resilient procedure use" experiment indicate that the STA had better overview when situated in a room watching the crew on video, without interacting with the crew. Given the importance of the STA role and the ability of giving independent advice to the crew, Kaarstad and Nystad (2020) chose this as the first topic in a series of studies looking into role independence, group work and teamwork. Kaarstad et al. (2020) describe the first experiment in which the location of the STA is manipulated to see whether this impacts her/his independence and also the crew performance. This is also described in Kaarstad et al. (2021). The study design used three manipulations as shown in Fig. 4.

The experiment was performed in HAMMLAB as a within-subject design with six planned participating crews. The analysis was changed to a more in-depth qualitative since four crews could not participate due to the Covid-19 pandemic. Kaarstad et al. (2020) thus already in the abstract warn: "Due to the small number of participants, we are not able to draw firm conclusions from this study." However, there are some interesting insights, especially as a basis for further studies and a motivation to complete this study. The findings were.

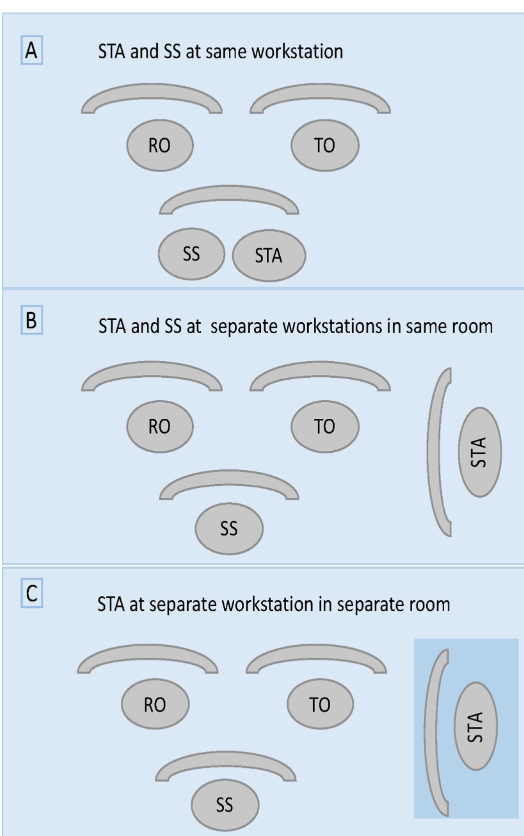

Fig. 4. Three experimental conditions of the STA study. From (Kaarstad et al., 2020, Fig. 1, p. 7).

- "Both the process expert ratings and the operator ratings showed that crew performance was better in condition A." (ibid., abstract).
- "the STA performed his role as described in the conduct of operations better when located in condition C than in condition A and B. It seems that when the STA is inside the control room, the operators include the STA in the crew and use him as an additional operator, which weakens his intended role as an independent advisor." (ibid., p. 26).
- "The operators preferred to have the STA in the same room, but in that condition, we observed that the STA was not used according to the requirements for the role." (ibid., p. 27).

The specific assigned duties to the STA that the process experts expected to be performed related to bullet two above, was to "maintain oversight" and "make recommendations" (ibid., Figure 7, p. 21). These kinds of results are intriguing and calls for more studies of confirmatory kind on this very topic, but also on similar related topics. All these dimensions are important when designing and training the STA role and the work processes that the STA and crew performs together in order to fulfil the prescribed role.

5. Implications for HRA

In this paper we have seen that new technology and crew roles do impact performance in handling accidents and incidents. This is of major importance for people designing the new technology, as well as people designing crew roles as specified in the conduct of operations and people designing the training programs. Another important aspect is the safety analysis. Which features in new technology and in crew work impacts safety, and thus should be essential to analyze in a PRA and HRA?

Features of new technology and teamwork is often used in arguments for robustness, and especially in safety arguments for recovery. Also, we need to take a closer look at the dependency issue in HRA.

Interestingly, Swain and Guttman (1983) in THERP already discussed recovery and dependency at length. Are these still a challenge? A lot has been done through the years on various aspects of HRA. However, many HRA methods still use Swain's dependency model. This shows both that the model makes some sense, but it also underlines the difficulty in finding a better method, and the need is recognized at least to make it more granular, based on the current knowledge of teamwork. Xing et al. (2020, p. 4-5) also emphasize recovery and dependency as two important areas for further development and research related to IDHEAS-ECA. Below is a discussion of how these topics are influenced by teamwork and crew roles.

5.1. Recovery and teamwork

What is the impact of teamwork and crew roles on recovery? To what extent can certain combinations of new technology and conduct of operations credit recovery?

Crew work and the fact that there is more than one member in the crew, should contribute to robust operation due to mechanisms and effects such as second checker, three-way communication to improve the crew situation awareness, and team briefings and updates. The control room with its teamwork in the crew, procedures, and HSI has occurred to be very robust to human errors, much more than error rates for single persons should indicate. For HRA, plants would typically credit the effects of these robust mechanisms in the crew to recovery. Recovery of human failure events is typically evaluated after the initial human error probability taking into account such effects.

Given the above observations, then the question comes up: How can the crew members' roles be accounted for in the evaluation of recovery, if e.g., the STA does not function as independent advisor but more as a procedure progression checker? And more importantly, how should the plants implement and train the STA and other crew roles such that they really work? For HRA practitioners, knowledge about what works and what might not work is essential in order to be able to judge whether diagnosis or action error recoveries can be credited or not.

This type of knowledge is not only important for the STA role, but also for other work processes in the crew. These factors are sometime denoted “command and control”. For example, the group processes earlier mentioned, dangers of group think, efficacy of proper task delegation by the shift supervisor, and effects of various strategies of crew briefings, are all important for the safety of the plant, and thus also important knowledge for people analyzing safety.

5.2. Cognitive dependency

Cognitive dependency is the mechanism that when the operator fails a first task, she/he is more likely to a make an error on a subsequent related task. This phenomenon is often considered in HRA, especially related to recovery actions. The most popular treatment of this in HRA is the one specified by Swain and Guttmann (1983) in the THERP method. The following dimensions are treated in this evaluation: Same or different crew; close or not in time; same or different location; additional cues or not. The evaluation of these will lead to a judgement of zero, low, moderate, high or complete dependency between events. If the dependency is high, the analyst must increase the probability for human error on the subsequent event. THERP outlines an exact recipe for this, which Gertman et al. (2005) adopted in SPAR-H and made a detailed flowchart as part of this method (ibid., p. A-7).

Xing et al. (2021) have in their new HRA method “The General Methodology of An Integrated Human Event Analysis System (IDHEAS-G)” approached dependency in a slightly different and more thorough way than earlier considered in HRA. They look at three types of dependency: Consequential dependency, in which the outcome of a human failure event (HFE) directly affects the performance of subsequent HFEs by e.g., time availability; Resource-sharing dependency; and Cognitive dependency (ibid., p. 4–38). In the traditional treatment of dependency in e.g., THERP and SPAR-H, the HEP of the dependent HFE is directly adjusted based on the model. Xing et al. decided to look more into the dependency context and model each part of this. This is done by a detailed evaluation of whether dependency exist, and if so, the new context is used for the dependent HFE and the HEP is recalculated including the new context (ibid., p. K-10). This way they may treat many subtleties in the way one HFE affects the subsequent HFE.

There are still unresolved issues in the treatment and modelling of dependency in HRA. The teamwork and crew role topics such as role independence between crew member roles as described in this paper is essential in order to be able to treat dependency correctly in a safety analysis. For example, if the STA works truly independent of the rest of the crew and the shift supervisor, will that have the same effect as when a new crew comes into the control room? This should probably be included into the modelling of dependency in modern HRA. Xing et al. (2021) can treat such effects in their model in IDHEAS-G. However, they still need empirical evidence as a basis for how to treat it in the analysis. Another question is how group processes are implemented in the crew. Are new compact control rooms built in a way that promotes closer contact and group think effects? Are there other artifacts in modern control rooms, e.g., automated checks, that can be used to decrease cognitive dependency between events depending on the work processes in the crew? What kind of work processes should be prescribed and trained to counteract any such plausible effects? There are numerous questions about teamwork and crew resource management that if they were resolved could improve the treatment of dependence in HRA.

5.3. Generalization

There is a great extent of configurability when using basic vendor designs to implement new control rooms. Digital control room solutions are flexible by nature, and many different control rooms can be the result of the same basic design proposed by a vendor. Thus, one must evaluate the link between the chosen technical solutions and the crew roles and teamwork as implemented by the plant. E.g., the way in which a large overview screen impacts crew performance may be dependent on how the crew utilizes it in its work processes.

One conclusion based on this is that the basic methodology for evaluation of new systems should follow the NUREG-0711 (O’Hara et al., 2004) guidelines and do proper integrated system validation (ISV) of each final control room in a simulator. It is not enough to validate the general design, but the final implementation must be validated together with its trained crews. A goal in the future would be to link ISV closer to HRA. However, not all PRA scenarios will be evaluated in ISVs. Thus, in order to generalize to these scenarios, and to estimate the human error probabilities for PRA, we still need to perform HRA.

For HRA, the generalization issue raises several questions. Firstly, for which methods and situations and factors can we use what data? Are the underlying data for the HRA methods valid for the new plants? Are there new error mechanisms in modern control rooms? Can we use data collected at one type of plant to influence the analysis of another plant? Many of these questions need to be evaluated for each method and some of the questions need to be answered for each analysis.

The role of HRA methods is to some extent to generalize from general knowledge to specific situations at specific plants with specific conduct of operations. Subjective expert judgement will then play a role at one level or the other. Thus, the knowledge of the HRA practitioners is still a crucial point.

For the HRA methods themselves, as well as for practitioners using them, it is important to obtain a thorough understanding of the nature of tasks using modern computerized systems and potential error modes and failure mechanisms as well as performance shaping factors. This then includes the link between crew roles, teamwork and the technology. Diversity of modern systems and their configurations will be challenging, particularly as configurability will be simple and quick. So, there must be a way for analysts to understand the important dimensions and be able to utilize the method to analyze those.

5.4. How to implement teamwork and organizational factors in HRA

Given the empirical results on the relation between teamwork and performance referred in this paper, how should teamwork and other organizational factors be taken into account in HRA?

Some teamwork issues have been discussed above when discussing dependency and recovery, e.g., the presence of a second checker when a member of the crew performs a task. The way in which this can be taken into account depends on the HRA method. Some HRA methods have PSFs that one can use to credit this kind of support directly. However, since teamwork covers quite a broad range of activities and dimensions, it can be difficult to assess how some of these dimensions impact human performance. For other organizational factors this is even more difficult.

The analyst should know the way in which the teamwork dimension impacts operator tasks in the HFE and scenario in detail. If the teamwork PSF specifies this, it can be used as a direct PSF on the task and HFE under analysis. Then it will impact the HEP directly. If the teamwork PSF or other organizational factors are more generic and it cannot be directly related to tasks in the scenario, one should take care to use this as a general, overall PSF. Rather, one should evaluate the impact of such organizational factors through other PSFs. For example, in the complexity and teamwork example in section 3.1, one could use knowledge about the teamwork dimension “backup and support” to evaluate the complexity PSF for the task evaluated. This would give a more precise and founded HEP than utilizing general values for both the complexity and teamwork PSFs. In the latter case one could end up on the same HEP, but one would not know what caused the extra complexity through the teamwork, and thus lack justification and knowledge for error recovery. The same example could be made for a general safety culture PSF. Instead of giving a safety culture PSF an overall rating, the analyst could use the knowledge of safety culture and how it would impact e.g., training, and then use the training PSF to account for this effect.

The point is to account for effects that are directly relevant for operating crew's work on the sharp-end scenario. In the analysis one will have to evaluate and avoid double-counting. This is easier to do if one is required to consider the sharp-end effect of organizational factors through PSFs that are possible to operationalize on the scenario.

Anchor points and examples would be important for such evaluations of additional impact of organizational factors on PSFs. For example, rather than overall measures of safety culture, concrete dimensions such as aspects of following safe job prescriptions, could be directly described, e.g., how they would impact a training or knowledge PSF.

This treatment of organizational factors as PSFs is similar to advice for the application of other PSFs to specific HFEs: One should be able to explain the way in which the PSF influences the detailed task of the operator or crew. For example, when evaluating a "procedures" PSF, one should explain how the procedure support the specific goal of the task, not just evaluate the overall procedure quality.

6. Conclusions

We have in many studies seen that teamwork is likely to be impacted by new technology. One aspect of this is the balance between humans and automation. Another is how the new technology introduces other ways to operate in the control room. Both introduce the potential for new and unexpected error mechanisms. Therefore, in addition to HSI design, the plant conduct of operations, the roles of crew members and their training are important for mitigation of these new error mechanisms. Thus, safety analysts need to understand which roles the crew members have and how this is trained and followed up.

This paper focused on the way in which new technology may impact human performance, as well as how crew roles and teamwork impact human performance in a control room. Recent experiments in HAMMLAB point to the fact that it is not enough to analyze the new technology. Unexpected side effects of new technology may be present. Thus, it is also important to analyze the work processes as described in the conduct of operations under which the new technology is taken into use. We have seen that the combination of the new technology and how it is used by the crew is decisive for the performance of the joint system, the crew and technology. So, both must be evaluated in order to understand the impact on performance. This is valid both for empirical validation as well as for predictive analysis as in HRA.

HRA is still needed for safety analysis, and there are still open research issues, such as recovery and dependency. Are the dimensions of time, same crew, new cues etc. sufficient to adjust for dependency in the new control rooms? As we have seen in this paper: For recovery it is a fundamental question of the degree to which plants can credit their work processes in the crew for recovery and mitigation of plant disturbances and accident handling. Teamwork and organizational factors can be implemented in HRA, if the dimensions have concrete applicability for the analyzed tasks. They can then be applied as separate PSFs or through other PSFs.

Data, and knowledge, is needed to support HRA. This is the fact for new digital systems and modern control rooms, as well as for new ways of human – technology configurations.

This paper has focused the discussions around the safety analysis side, especially regarding HRA. Needless to say, the topics are as important and interesting in a design and operations point of view. Identifying issues related to design of the new I&C systems for NPPs are important for vendors, in order to improve their basic design, and they are important for NPPs, in order to improve their final applications and configurations of the new systems. Identified issues about crew roles and teamwork are even more important for operating NPPs, since they can actually change the role descriptions, the work processes and the training in an operating plant. These topics are thus even more important in order to improve the safety of the existing fleet as well as the future fleet of nuclear power plants in the world.

Finally, the importance of empirical knowledge, data and information as can be provided by HAMMLAB and similar research labs cannot be underestimated. This is underscored by the use of empirical data in modern HRA methods such as IDHEAS-ECA.

CRediT authorship contribution statement

Andreas Bye: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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