



Original Article

Human Reliability Analysis for Digitized Nuclear Power Plants: Case Study on the LingAo II Nuclear Power Plant

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ABSTRACT

The main control room (MCR) in advanced nuclear power plants (NPPs) has changed from analog to digital control system (DCS). Operation and control have become more automated, centralized, and accurate due to the digitalization of NPPs, which has improved the efficiency and security of the system. New issues associated with human reliability inevitably arise due to the adoption of new accident procedures and digitalization of main control rooms in NPPs. The LingAo II NPP is the first digital NPP in China to apply the state-oriented procedure. In order to address issues related to human reliability analysis for DCS and DCS + state-oriented procedure, the Hunan Institute of Technology conducted a research project based on a cooperative agreement with the LingDong Nuclear Power Co. Ltd. This paper is a brief introduction to the project.

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1. Introduction

The control room (MCR) in advanced nuclear power plants (NPPs) has changed from analog to digital control system (DCS) [1,2]. The operation and control have become more automated, centralized, and accurate due to the digitalization of NPPs, which has improved the efficiency and security of the system [3]. Compared with the traditional control system, which was based on analog techniques, the digitized system has led to some new and more complex issues in terms of human factors, such as: (1) the human–machine interface (HMI) of the MCR has become more diversified and

concentrated; (2) operators' behaviors, tasks, operation mode and workload have changed dramatically; and (3) the team structure and operating mechanism are significantly different [4]. Meanwhile, many NPPs that have adopted DCS have changed their operating procedures in terms of principles and structural aspects. For example, there are event-oriented procedures, which are based on a single event that develops into state-oriented procedures (SOP), which are based on the physical state of the NPP. New issues related to human reliability inevitably arise due to the adoption of new accident procedures and the digitalization of the MCR in NPPs. All of these changes have the potential to induce negative impacts

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on operator performance, and new error modes and risks may appear.

Organizations and experts worldwide have noted problems related to human factors after NPPs underwent digitization. Many studies have been conducted on this problem. For example, the US Nuclear Regulatory Commission has sponsored research at Brookhaven National Laboratory to better define the effects of changes in human–system interfaces, brought about by incorporating digital technology, on personnel performance [5–7]. The Electric Power Research Institute Human Reliability Analysis (HRA) Users Group suggested that some additional modifications and considerations must be employed when the current HRA approach and models are applied to systems with digital controls [8]. The Korea Atomic Energy Research Institute has studied some issues related to soft control, situation awareness, cognitive workload and human error probability in NPP advanced MCRs [9–12]. Reference [13] provides a detailed overview of the Halden benchmarking study, which discussed the applicability to DCS.

By contrast, compared with traditional NPPs, digital NPPs incorporate many changes, such as changes in organizational structure, characteristics of human factors, the HMI and the system features of DCS + SOP. The methods of HRA for analog MCRs cannot meet the requirements of HRA for DCS and DCS + SOP. Hence a new HRA method that can consider the characteristics of DCS and SOP needs to be proposed.

The LingAo II NPP is the first digital NPP in China to apply SOP. This study was initiated in January 2010 to address issues related to human reliability. This project lasted for 5 years and ended in December 2014. This project had three purposes. The first was to establish a methodology and model of HRA for DCS + SOP. The second was to identify possible new human reliability issues and to determine potential unknown risks for operators under accident conditions. The last purpose was to propose an HRA model for the LingAo II NPP and to complete the HRA.

This paper is a brief introduction to the project. In section 2, we introduce the framework, methods, and design of this research. In section 3, we present some results of this project. Section 4 includes the discussion and conclusion.

2. Research framework and methods

2.1. Research framework

According to the main objective of this project, there were theoretical and applied research work that needed to be completed. This included five tasks. The first was to analyze operators' behavior characteristics in a digital MCR, such as the changes and features of human cognitive behavior, team cooperation and communication, operators' error mode change, and root cause analysis of typical human factor events. All of these tasks helped in the identification of possible human factor issues related to DCS + SOP technique application. The second task was a series of specialized simulation experiments and laboratory experiments that were conducted to verify the results obtained in the tasks just mentioned and to collect data. The third was to develop

methodologies of DCS + SOP-HRA, which included the method and model of DCS-HRA, the method and model of DCS + SOP-HRA, the database system of DCS-HRA, and the analysis software system of DCS-HRA. The fourth was to prepare the HRA report for the LingAo II NPP. Finally, a proposal was submitted for a comprehensive program to prevent human error.

2.2. Research methods

The research methods included qualitative analysis, experimental research, and quantitative analysis. The specific technical methods included investigation of operator behavior patterns and characteristics via behavioral observation, questionnaire survey, and comparative analysis. Simulation experiments and human factors engineering experiments were carried out to investigate the factors and mechanisms affecting operators' cognitive behavior. An operator cognitive behavioral model was constructed using qualitative analysis, modeling, and simulation techniques. Human reliability data were obtained using a testing method, statistics method, expert judgment, review of original data, and extrapolation.

In order to reflect the operator's cognitive changes in the digital MCR, and in order to model the operator cognitive behavior models, we integrated several different modeling techniques. For example, we applied the Markov Chain for the modeling of the operators' monitoring model; the Bayesian belief network and fuzzy cognitive map were used to construct the operators' situation assessment model and response planning model; and the operators' response implementation model was based on the event tree.

For the purpose of ensuring the applicability of the research results, this project emphasized use of the simulator of the LingAo II NPP MCR as a reference. The new HRA method we developed has been applied to this project.

3. Results

This paper presents results only with respect to the operators' behavioral characteristics in the digital MCR and the methodology of DCS-HRA. We discussed the changes in and features of human cognitive behavior, team cooperation and communication, operator error mode change, and the DCS + SOP-HRA model.

Behavioral observation is a basic method for studying human behavioral characteristics. The purposes of behavioral observation in this project were to determine changes of operator behavior with respect to the traditional MCR and to identify possible error modes. The research team completed behavioral observation for more than 10 operating crews in the LingAo II NPP MCR, for a total of approximately 50 hours. Recording and behavioral observation for a total of 600 hours was done for 20 operating crews in a full-scope simulator of the LingAo II NPP during requalification training. The scenarios included normal operation and accident scenarios. We conducted interviews for the operating crew after each observation.

During normal operation, operator behaviors contain a large number of skill-based (SB) and rule-based (RB) behaviors.

All of these behaviors are basic units of plant operator behavior. Meanwhile, these basic units form the basis of knowledge-based (KB) behavior. Therefore, collecting and studying human factor events with respect to SB and RB was the first step to developing a human error prevention program. In addition, we needed to analyze more complex human factor events with respect to KB. Analyzing these types of human factor events helped us to understand the transformation from events led by SB and RB personnel behaviors to events led by KB personnel behaviors. Furthermore, the study provided a basis for developing a higher-level human error prevention program.

Although there were many SB and RB personnel behaviors during normal operation, it was very hard to observe and record them. The researchers initially tried to obtain these data by analyzing the event reports, but there was not much valuable information found after analyzing about 100 reports, because these reports were not focused on human factor issues. Later, we found small deviation reports that seemed like diary reports written by operating personnel. This type of report recorded the consequences of failures that were observed by operators during operation, such as when they pressed the wrong button, input the wrong number, or directed the system to the wrong screen. These diary reports also recorded situational factors and operators' own psychological process. After group discussion, we believed that these small deviation reports were very useful for studying human error mode and mechanisms. We collected more than 400 reports. The following were the main results.

3.1. Changes of operator behavioral characteristic

HMIs have changed dramatically after the digitalization of MCRs; the ways in which operators access information, and the display of information, have also changed. These factors have changed the ways in which operator access, store, process, and output information, which means operator cognitive behavior has changed greatly.

- The main impacts of digitalization on MCR operators were the following: operators' cognitive load has gone through a great change compared with that for traditional MCRs; operator roles and functions have changed in the operating crew; the mechanisms of communication have changed among team members; operator behavior patterns have changed in performing procedures.
- The HMI of a digital MCR has expanded the sources of available data and provided operators with more available information about the system. Operators can combine this information in a more flexible way to determine the system state. Thus, the DCS has helped operators to reduce the cognitive load in collecting and integrating information.
- Operators have changed their roles in the total system from manual controllers to supervisors of an automated system. In the digital MCR, operators' primary tasks have changed from operation to monitoring and decision-making. The cognitive characteristics of tasks have been increasing.
- Operators' cognitive behavioral process consists of four stages: monitoring and detection, situation assessment, response planning, and response implementation. In order to complete these tasks, operators needed to perform interface management tasks, which increase the cognitive load and working load of operators. This has increased the chance of human error occurring, such as loss of situation awareness and mode confusion.
- Due to the increase of cognitive load, operators have usually implemented some operational strategies, which have brought new risks during performance of primary tasks, such as decreasing information verification and focusing on specific operations.
- Errors of commission (EOC) have seen a significant increase. The display and distribution of information in the digital MCR more easily lead to errors of omission (EOO).
- The operators have strong preferences, such as ignoring some procedures habitually.
- The DCS has had significant impacts on operating crews in five aspects: team performance, communication, situation awareness, electronic procedures and secondary task management.
- When the operators were performing the SOP, the workloads of monitoring and response implementation were both significantly higher than were those of situation assessment and response planning. There was no significant difference between monitoring and response implementation, or between situation assessment and response planning.
- In the LingAo II NPP MCR, each operator has their own workstation. Operating behaviors are hard to observe by other operators (unless the mistake leads to feedback). The number of human factor events has relatively increased due to the lack of supervision.
- The main factors influencing operator performance were found to be interface management, the complexity of the system, communication, the limited presentation of the procedures and system screen, familiarity with the system and the operating experience of the operators and crew.
- During the recording process, we observed 13,276 instances of monitoring transfer in total. Operator monitoring behavior mainly includes three types of transfer: procedure transfer, abnormal transfer, and communication transfer. Procedure transfer indicates an operator monitoring transfer caused by system procedures; the percentage of this type was 36%. Abnormal transfer indicates an operator monitoring transfer caused by an alarm or parameter change when the system showed an abnormality; the percentage of this type was 14%. Communication transfer indicates an operator monitoring transfer caused by a reminder from another operator; the percentage of this type was 29%. The percentage of other types of transfer, which could not be grouped into these three types, was 21%.
- We investigated the process of operator cognitive behavior, and the factors and mechanisms that influence operator cognitive behavior. The cognitive behavior model MAPI-B was constructed for operators in the DCS. This model integrated a monitoring model, a situation assessment model, a response planning model and a response implementation model. Fig. 1 illustrates the process of operator monitoring behavior. Fig. 2 is the operator monitoring

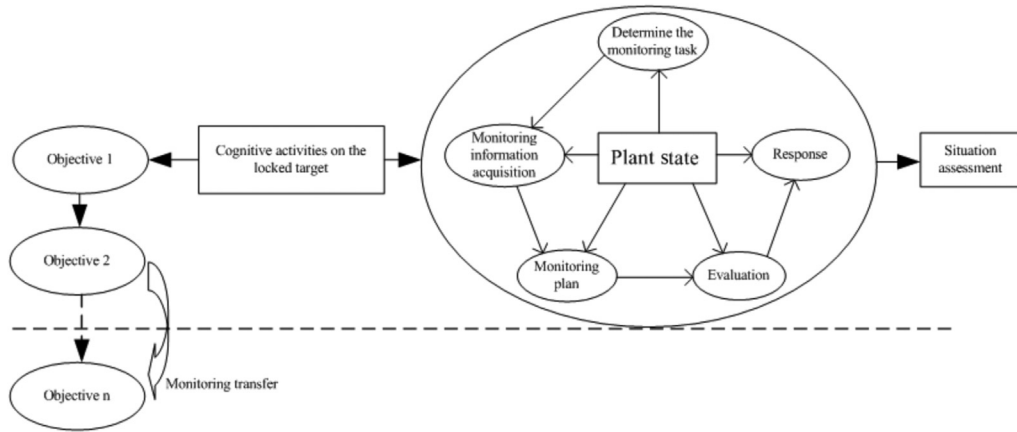


Fig. 1 – Process of operator monitoring behavior.

model. Fig. 3 is the operator situation assessment model. Fig. 4 is the operator response planning model.

3.2. Team cooperation and communication in digital MCR

The DCS resulted in changes of organizational structures and operating mechanisms for the crew operating in the MCR; these changes included operating crew constitution, relationship between operators, task allocation mechanism, etc. This project was focused on problems in the digital MCR associated with crew structure, operator responsibility, network and frequency of communication, characteristics of communication content, communication patterns, communication failure distribution, and features and impact on human error of communication patterns.

Based on the observation and on the analysis results, the frequency of communication between operators might be reduced in a digital MCR, but the efficiency of communication might be higher. There was more communication among the operating crews when important decisions had to be made. Operators received system information from different perspectives and formed a good team. Fig. 5 is a schematic of the network and frequency of communication among operating crew members.

We carried out experiments in a full-scale simulator of the LingAo II NPP to investigate the characteristics of

communication content, the communication patterns, the communication failure distribution and features, and the impact on human error of the communication patterns. The experimental scenario was a main steam line break superposition of a steam generator tube rupture. Five operating crews were involved in the experiment. Video equipment and audio capture devices were used to record the whole experimental process. Tools and software were used to analyze these materials. We found that the timeliness of communication, means of communication and content of communication were three important factors that influenced the efficiency of the communication of the operating crew members. The state parameter of the NPP, the system function, the equipment and the procedures were the main contents of communication when operators were performing the SOP. Communication about the parameters took up the largest proportion among the types of communication; this reflected the characteristics of the state-oriented and nonspecific accident of the SOP. The main patterns of communication were inquiry, statement, reply, suggestion, and call. The inquiry mode was associated with the parameter, procedure, system function, and equipment; the call mode was associated with the procedure. Lack of communication with respect to inquiry and judgment of parameters increased the burden on operator attention resources. This affected the decision-making of the operating crews.

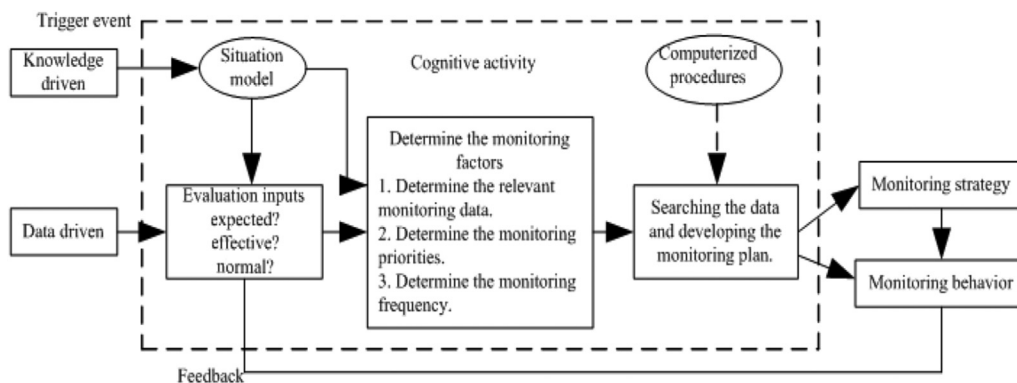


Fig. 2 – Operator monitoring model.

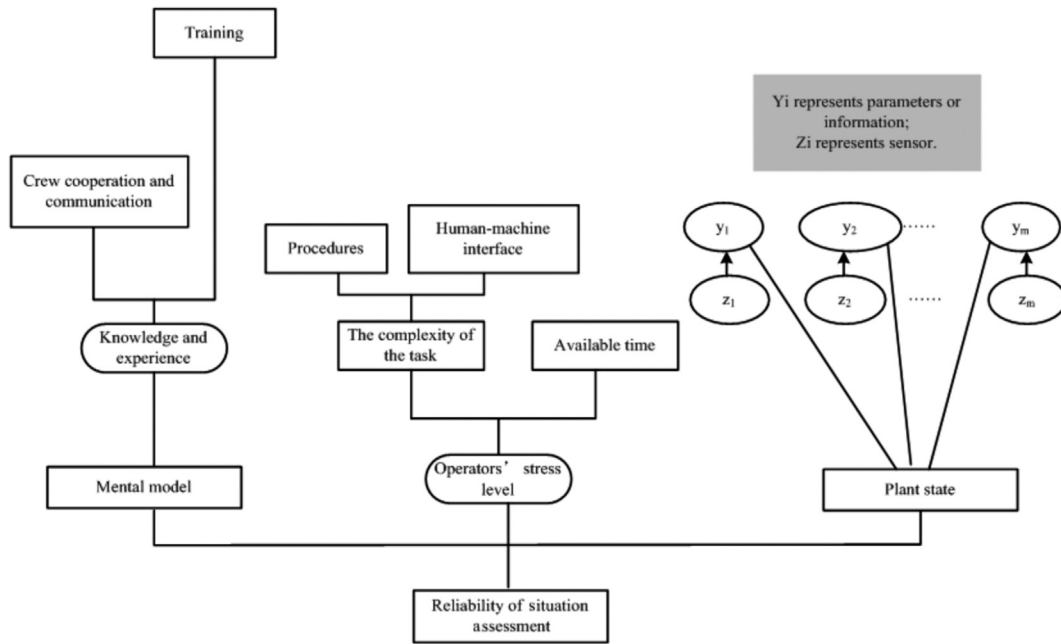


Fig. 3 – Operator situation assessment model.

3.3. Human error mode changes in digital MCR

We studied seven types of personnel behavior that had low cognitive level, including operation error, procedure performance, communication, panel surveillance, HMI, input error and alarm response. Meanwhile, we also investigated KB behavior that had a higher level of consciousness in the DCS.

- Each stage of monitoring, situation assessment, response planning and response implementation may involve human error. This project divided the 39 types of human error into five categories. There were seven types of monitoring error, five types of situation assessment error, three types of response planning error, six types of response implementation error, and 18 types of interface management error.

- Among 500 event reports, there were 428 event reports related to human error and small deviation reports. The type and proportion of errors are shown in Table 1.
- Some operators' SB behavior in the traditional MCR (such as pressing the button) might have changed to KB behavior, which requires a higher level of consciousness. Errors related to this type of behavior could not be attributed to slips or lapses [14]. In this project, we called this new human error mode KB-SLIP. Other new human error modes were also found in digital MCRs, such as errors of page configuration, mistaken clicks of the mouse, data entry errors, errors of target identification, and errors of information gathering.
- According to the THERP [15], when the operator was performing tasks, the main error mode was EOO. However, based on the research data, EOC had a more significant

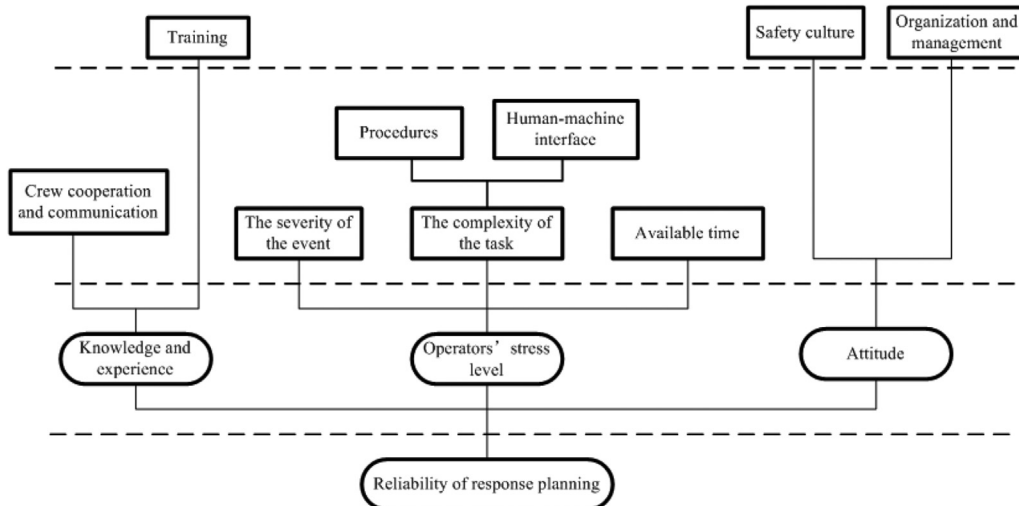


Fig. 4 – Operator response planning model.

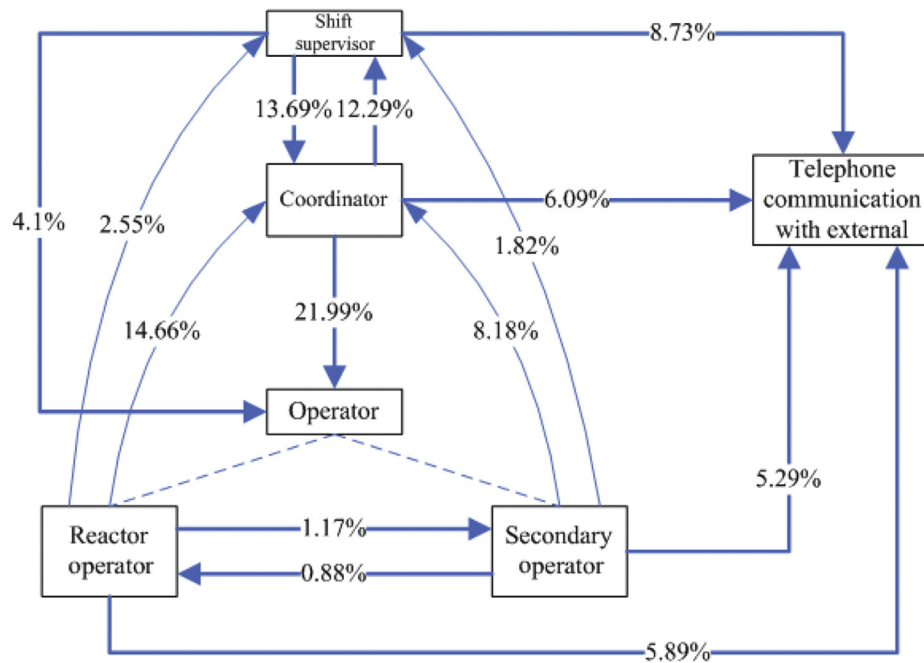


Fig. 5 – Network and frequency of communication among operating crew members.

contribution due to the display control features of DCS. EOCs accounted for 59% of overall errors and the percentage of EOOs was 21%.

- Most of the reasons that EOOs occurred in the DCS were *procedures take too long to perform or complex form for performing procedures*.
- Interface management tasks had a big impact on human error. If an interface was mismanaged, the *enormous information with limited display area* would be changed to *enormous information with limited acquisition* for operators, and this led to some information being missed that operators had needed to obtain when performing the tasks. Cognitive load and working load were increased because of interface management tasks, which resulted in a rise in the possibility of both EOO and EOC.

3.4. DCS + SOP-HRA methodology

Considering the features of DCS, SOP, and DCS + SOP, we established the DCS-HRA methodology, which included the

Table 1 – Type and proportion of human error.

Type	Proportion
Work preparation	9.5%
File management	15.8%
Work practice	18.8%
Operation error	6.7%
Procedure performing	6.1%
Communication	10.7%
Panel surveillance	4.2%
Human–machine interface	5.8%
Input error	1.2%
Alarm response	2.1%
Others	19.1%

operator cognitive behavioral model MAPI-B, the reliability quantitative model of operator cognitive behavior MAPI-Q, the behavioral model of the operating crew MAPI-T, and the behavioral reliability quantitative model of the operating crew MAPI-TQ. The MAPI-B model was used for qualitative analysis of operator behavior. The MAPI-Q model is a quantitative analysis model for operator behavior. The MAPI-T model was used for qualitative analysis of behavioral of operating crews. The MAPI-TQ model was used for quantitative calculation of behavioral reliability of operating crews. The MAPI-T and MAPI-TQ model were an engineering application model specialized for DCS + SOP.

3.5. Engineering application

For the LingAo II NPP, this project used the MAPI-T and MAPI-TQ model to analyze 37 human factor events. The HRA report for the LingAo II NPP for the construction design phase used the Standardized plant analysis risk–human reliability analysis (SPAR-H) method [16]. Comparing the results of the SPAR-H method and the MAPI method, we found that the human error probability calculated using the MAPI method was lower than that calculated using the SPAR-H method, which means that the new method overcomes the disadvantages of the overly conservative SPAR-H method. The new approach reflects differences in human error probability for the same human factor event at different accident backgrounds. The new approach that we have proposed includes a more comprehensive analysis of operator cognitive processes. It can reflect cognitive weaknesses of operators when they deal with accidents. Based on our results, we also provide specific advice for operator training and plant improvement.

4. Discussion and conclusion

Digital control systems are being used in new, advanced nuclear power plants in China, such as Generation II (e.g., CNP-600), II+ (e.g., CRP-100) reactors, and Generation III reactors (e.g., AP1000) [17]. In addition, DCS is being implemented in older plants as these are upgraded. Since DCSs were adopted in NPPs, some features related to these newer systems have presented challenges for the HRA. The current HRA models were developed before the development of these digital systems, and thus may require new analysis models to properly assess the impact and risk of the digitalization of NPPs.

This project first systematically studied human reliability issues associated with the DCS; then, it investigated the impact of DCS + SOP on the operators. To date, certain results have been applied at the LingAo II NPP as a case study. Compared with traditional NPPs, there were some significant changes in the LingAo II NPP, such as that the operator monitoring model changed from one that was knowledge-driven to one that was data-driven. As we described earlier, the characteristic of the LingAo II NPP is DCS + SOP; all results were based on this model. So, if we wish to extend the results to the other NPPs, for example an NPP adopting DCS + event oriented procedure, we believe some of the results should be revised. We will continue to improve the theories, methods, and models during the engineering application process.

Conflicts of interest

All authors have no conflicts of interest to declare.

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Abbreviations

DCS	Digital control system
EOC	Error of commission
EOO	Error of omission
HMI	Human–machine interface
HRA	Human reliability analysis
KB	Knowledge-based
MCR	Main control room
NPP	Nuclear power plant
RB	Rule-based
SB	Skill-based

SOP	State-oriented procedure
SPAR-H	Standardized plant analysis risk–human reliability analysis

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