Introducing Human Performance Modeling in Digital Nuclear Power Industry

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Abstract. Human performance modeling (HPM) can be used to explain and predict human behaviors under certain situations, helping designers in the design stage through evaluating the interface, procedure, staffing, etc. This study discusses the feasibility of introducing HPM methods into digital nuclear power industry through 1) the new characteristics of human- system interaction/human performance in digital main control rooms (MCRs) of nuclear power plants (NPPs), 2) the simulating abilities of available HPMs on their latest progress. Based on the review of the two issues, we conclude that: 1) digitalization of NPPs changes operators' performance through the system, task, environment and human himself. 2) HPM is classified as human reliability modeling and cognitive modeling. The lack of performance data could be an obstacle for applying human reliability modeling in digital MCRs. The unclear underlying mechanism of human-system interaction in digital MCRs constrains the introducing of cognitive modeling.

Keywords: Digitalization, Nuclear power plants, Performance influence factors, Human performance modeling.

1 Introduction

Safe operation in NPPs can never be emphasized too much. While human performance act as a key component in this safe operation (O'Hara, Brown, Lewis, & Persensky, 2002; O'Hara, Higgins, Persensky, Lewis, & Bongarra, 2004), Much attention has been paid on this topic to enhance human reliability or error-tolerance of the system. Since it's difficult to obtain the real data of operators' performance in NPPs, especially under emergency conditions, introducing Human Performance Modeling (HPM) methods to predict operator performance seems to be important and necessary. What's more, the digitalization of NPPs changes the way of human-system interaction, which may cause new challenges for introducing HPM in such complex system. Meanwhile, methods for modeling human performance also got development during these years. Their powerful modeling ability impressed researchers very much. To identify the opportunities and challenges of applying HPM in digital MCRs, this paper presents a review on the new characteristics of human-system interaction/ human performance in digital MCRs first.

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2 Digitalization and Human-System Interaction in MCRs

The shift from analog to digital NPPs changes the way of human-system interaction, mainly through four main aspects: system, task, environment, and human.

2.1 System

The digitalization in NPPs changes the system directly, reducing equipment volume, simplifying cabling, and supplying new functions (Cou, 1997). Three important trends of digitalization have been claimed: increased automation, computer-based information display and intelligent operator aids (O'Hara & Hall, 1992; Kim & Seong, 2009). They overlapped with each other in some extent:

- **Automation** means to allocate functions to machine agents instead of original operators (Parasuraman, 1997). Different levels of automation (LOA) differs from each other in their task allocation between human and machine under the four cognitive processing stages: monitoring, generating, selecting, and implementing (Endsley, 1999) or information acquisition, information analysis, decision selection, and action implementation (Parasuraman, Sheridan, & Wickens, 2000). The LOA needs to be considered carefully when deal with certain tasks: a higher LOA decreases operation time and workload in the shutdown reactor task but not in the reset alarm system task (Jou, Yenn, Lin, Yang, & Lin, 2009); an intermediate LOA (completely automatic in implementing stage but semiautomatic in other three stages) is better than a lower (action support) or a higher LOA (supervisory control) for one’s SA in the procedure tasks (Lin, Yenn, & Yang, 2010). Beside, Automation in monitoring and implementing stage such as the pre-alarm system (Hwang, Lin, Liang, Yau, Yenn, & Hsu, 2008) and the auto-reset model alarm system (Huang, Hwang, Yenn, Yu, Hsu, & Huang , 2006, Huang, Lee, Hwang, Yenn, Yu, & Hsu., 2007) enhanced human performance and reduced operators’ workload in monitoring tasks. On the other hand, automation may cause human errors due to poor feedback, inadequate transparency, or operators’ over reliance on automation (Kim & Seong, 2009). What’s more, lack of appropriate automation, misunderstanding or mistrust automation could cause accidents (Schmitt, 2012).
- **Computer-based information displays** indicate advanced display forms to provide new possibilities for information organization and presentation (Kim & Seong, 2009). Four types of information organization methods are used to design displays in MCRs (Andresen, 2011): Conventional process mimic display (organized by process flows), Task-based display (organized by predefined tasks), Ecological display (trying to make information easy to retrieve and utilize from the work environment), and Function-oriented display (refer particular to safety-functions). Ecological interface design (EID) is the most studied topic: Designers use the abstraction hierarchy method (AH, Rasmussen, 1985) to select and organize information, and present them in advanced configural forms. A number of studies found that ecological interface improving operator’s monitoring (e.g. Burns, et al., 2008) and diagnosing performance (e.g. Ham, Yoon, & Han, 2008), especially

under the novel and complex scenarios, and also enhancing operator's SA (e.g. Kim, Kim, Jang, & Jung, 2012), reducing their workload (e.g. Lau, Jamieson, Skraaning, & Burns, 2008), but taking more spatial resources of operators (Pawlak & Vicente, 1996).

Automation can coexist with computer-based information displays through one item — computer-based procedure (CBP). It's a digital method to support procedure management. There are four LOA of CBP: manual, advisory, shared, and automated (O'Hara, Higgins, Stibler, & Kramer,2000). Integrated decision support information at the decision point in the CBP (the advisory level) and automation execution such as judging the current condition with the given standards (the automated level) are identified to improve one's performance and reduce the workload and behavior error (Huang & Hwang, 2009; Lee & Seong, 2004). Meanwhile, information presentation of CBP based on text or flowchart, two-column format or three-column has also been discussed. Xu and her colleges (2008) found that one- and two-dimensional flowcharts are better than two-dimensional flowcharts in skilled task.

2.2 Task

Tasks are "Procedures and characteristics" (Kim & Sung, 2003, P485) that operators need to implement. Since digitalization helped to complete many motor actions and supplied operator aids, less motor activities but more cognitive activities are required. Researchers believe that introducing computers to support the operation even changes operators' work roles. Sheridan (1997) postulated that planning, teaching, monitoring, intervening and learning are the new work roles of operators in this computer-supported supervisory control system. Monitoring, intervening and high level cognitive abilities such as decision making (to decide when and how to intervening) are regarded as the most important works (Kim & Seong, 2009; O'Hara & Hall, 1992).

Besides, operators in digital MCRs need not only to implement the primary monitoring tasks, but also to manage the interface itself to get the demanding information. This task called "interface management task" includes configuring, navigating, arranging, interrogating and automating, which compete with the primary task for the cognitive resources and may cause primary task performance degradation especially when the time pressure is high (O'Hara et al., 2002). Zhou, Jiang & Zhang (2012) declaimed that interface management task is one of the most significant impacts on operators' cognitive reliability to influence their performance.

Accordingly, the way researchers treat tasks is also in change. A systematic perspective has been used to consider the relationship between the underlying factors and task complexity. According to Liu & Li's summary (2011), not only the characteristics of task itself (such as steps, task types) affect task complexity, but also the task-related information display on the indicator, the time pressure while operators completing the task, even the characteristics of task doer are regarded as task complexity contributors. Besides, High-complexity task induces performance degradation and human errors (e.g. Hwang et al., 2008; Kim & Jung, 2003; Xu et al., 2008).

2.3 Environment

The physical working environment, leader ship, team size, communication, etc. are all environment factors. Since digitalization made both Board operators (BOs) and Shift Supervisor (SS) obtaining higher level information from digital Human-system interfaces (HSIs) and controlling through the CBPs directly, they worked more independently from each other than in the traditional MCRs.

Communication amount and mode between operators have been changed: 1) The amount of communication decreased since many system information can get directly from the parameters on the interface; 2) More information-confirmation (know the content of wanted information, just ask for a confirmation) instead of information-identification (do not know the content of wanted information, ask for the detail contents) is used; 3) The asymmetric between SS and BOs has been compensated: SS needn't do as much integrate and disintegrate work as in the traditional MCR. 4) the variance of communication decreased, 5) communication is important for a crew to reach shared situation awareness (SSA) and corporate based on the SSA. Since the total amount and frequency of communication decreased sharply, operators may need additional communication or operation to keep the status of each other (Chung, Yoon, & Min, 2009; Kim, et al., 2012; Min, et al., 2004; Roth & O'Hara, 1999).

Besides, training and team size have also been discussed under digital circumstance. Training level (familiar extent) and training interval affect operator performance (Dong & Li, 2011; Xu et al., 2008). The non-technical skills training, such as crew resource management training, improved crew coordination and reduced operators' mental workload significantly (Crichton & Flin, 2004; Kim & Byun, 2011); Huang & Hwang (2009) found that two operators can complete tasks as good as three operators when assisted with CBPs in the digital MCRs.

2.4 Human

Cognitive abilities, personal status (e.g. emotion), personality, etc. are all individual factors related to human. All the changes mentioned above: LOA, EID, CBPs, interface management tasks, work role, task complexity, new communication mode and amount, training and team size will influence operators' behavior, workload, SA and personal status, and may finally changes operator's individual characteristics (e.g. visual ability) in a long run.

To conclude, human-system interaction has been changed through the four main aspects. In addition, system, task, environment and human factors are also supposed to be the four big factors influence human-system interaction, under both digital and traditional conditions, also called performance influence factors (PIFs) (Kim & Jung, 2003). This means the changed and unchanged PIFs in the four aspects will influence human-system interaction collectively. But how these factors influence human-system interaction integrally is unclear. Moreover, these four aspects factors mentioned above are sometimes overlapped with each other: e.g. the task complexity related factors may overlapping with factors related to human. In fact, the ambiguous and overlapping in PIFs category is very common (e.g. Chang and Mosleh, 2007a).

Thus, the changes of the four big factors under digital condition, the unclear boundary among these categories and the unclear mechanism or manner of PIFs influencing performance could raise challenges to the application of HPM.

3 Human Performance Modeling

HPM methods use mathematical or computational abstractions to explain and predict human behaviors in particular domains or tasks (Byrne & Pew, 2009). According to Pew's (2008) taxonomy with a historical viewpoint, two ways of HPM are introduced in this section, roughly recommended on their modeling mechanism and simulating abilities.

3.1 Human Reliability Modeling

Human reliability modeling is developed from HRA methods. The whole modeling process could be viewed as an extension of task analysis, therefore human reliability model is also named as task network model or reductionist model (Laughery Jr & Corker, 1997).

Systems Analysis of Integrated Network of Tasks (SAINT) is a typical human reliability model. First, Tasks (that need to cope with) are decomposed into elemental actions (such as scan, read or other behaviors) until the time and success probability to perform these actions can be accessed from a particular database. Then the elemental actions are organized in network or series of network. The relationships among these elemental actions (e.g. operation order) are defined upon results from task analysis. Through define the input, duration (can be adjusted by PIFs such as stress, fatigue), essentiality, type, class and output of the tasks, SAINT generates quantification results such as time, accuracy, and workload (Pritsker, 1974). There, PIFs affect human performance as adjustment factors.

Improved Performance Integration Tool (IMPRINT) uses the same software of SAINT, but can execute tasks in parallel and generate more informative workload (Mitchell, 2003). Human Operator Simulator (HOS) introduces cognitive micro–models such as perceptual and mental computation to model human performance (Harris et. al., 1989). In fact, as the importance of cognitive factors is increasingly recognized, more cognitive factors are brought into human reliability models. The COGnition as a NEtwork of Tasks (COGNET) model (Ryder, 1998) and the Information, Decision, and Action in Crew context (IDAC) model (Chang and Mosleh, 2007a) could be regarded as cognitive models already.

3.2 Cognitive Modeling

Cognitive models are developed on the findings and theories from cognitive science, especially the human information processing theory. The Adaptive Control of Thought-Rational (ACT-R) model is structured mainly with a perceptual-motor system, a goal module, a declarative memory module and a procedural memory module

(Anderson, Bothell, Byrne, Douglass, Lebiere, & Qin, 2004). With these modules and particular rules, ACT-R can model various functions such as perception, reasoning, decision making and learning (Anderson & Schunn, 2000). Other cognitive models are more or less like ACT-R. Most of them present sensory input, cognitive processing, and motor output as the major three stages of information processing, but differ with each other in many details, from basic cognitive structures to high-level functions. Characteristics of these models are discussed correspondingly with demands that digital MCRs put on operators in the following five aspects (adapt from Pew and Mavor's (1998) perspectives):

- **Basic cognitive structures and abilities:** indicating the structure of sense, perception, attention, memory and the corresponding functions. Since monitoring became one of the most important tasks in digital MCRs, a reliable and powerful modeling of human sensory and perceptual abilities could be necessary. Because of their outstanding theory base and well-constructed visual, auditory senses, attention (or cognitive resources) and memory, executive-process interactive control (EPIC, Kieras & Meyer, 1997), ACT-R (used the same perceptual module of EPIC) and Principles of Synthetic Intelligence (PSI) (Bach, Dörner, & Vuine, 2006) can meet the criterion.
- **High-level cognitive functions:** including reasoning, decision making, learning, planning (re-planning under a new condition), problem solving, etc. Decision making is important since operators need to decide when and how to intervene during monitoring. While the majority of the models make decisions directly based on the matching degree of goals and current conditions, The situation awareness model for pilot-in-the-loop evaluation model (SAMPLE) (Zacharias, Miao, Illgen, Yara, & Siouris 1996) and cognitive environment simulation (CES) (Woods & Roth, 1987) give more consideration of the inner condition that operators perceived, and make decision based on situation awareness (SA) and goals. Since SA is a popular concept in human factors studies, the use of SA made the modeling more directly to the results of human factor studies. In addition, ACT-R (Anderson & Schunn, 2000) and PSI (Bach et al., 2006) can model learning and planning abilities.
- **Team work:** As mentioned in section 2, communication, team size and training need to be considered when simulate crew operation. ACT-R, Man-machine Integration Design and Analysis System (MIDAS) (Gore and Corker, 2002), SAMPLE, and OMAR can simulate communication between crew members, but lack the information about other teamwork-related abilities. IDAC models teamwork though defining operator responsibility and communication rules (Chang and Mosleh, 2007a).
- **Influencing factors:** Factors affect human performance such as fatigue, emotion, motivation and age have been considered in some of the HPMs. Two ways are used to include these factors in modeling, one is to integrate the factors into the underlying mechanism (e.g. PSI), the other is to regard these influence factors as the successful probability of performing certain actions (e.g. IDAC). From section 2, we know that digitalization has changed many PIFs related to system, task and

environment and finally influence human performance. But the affecting mechanism or manner are still not clear.
- **Output or mediate output:** Plenty of useful outputs such as workload, situation awareness, timeline, accuracy of actions and even behaviors are generated for engineering application. MIDAS uses a virtual man "Jack" in 3D environment to present the behaviors, which makes the simulating process more impressing and understandable.

In summary, cognitive modeling can model a battery of abilities from perception to learning. Most of the abilities and functions required when operators work in digital MCRs can be modeled by cognitive modeling.

4 Conclusion

This paper focus on the new characteristics of human-system interaction in the digital MCRs to discuss the possibilities and challenges for introducing HPM into NPPs.

Since digital NPPs are not commonly in use, the lack of data support (i.e. the time and success probability to perform certain actions in a digital MCRs and how the influence factors adjusting the performance) could be the main obstacle for applying human reliability modeling in NPPs. Using data from other field like aviation or military (e.g. IDAC, Chang and Mosleh, 2007b) is a method worth trying. Thus, to consider the difference between different industries before using their database is necessary.

Meanwhile, cognitive models are good in modeling cognitive abilities and functions. Instead, the confusion of the mechanism that PIFs influencing operators' information processing is the real problem in introducing cognitive modeling method in NPPs. Until now, studies are mainly concern the superficial relationships between single PIF and human performance. Researchers need to pay more attention to find out how these factors interact with each other and the underlying mechanism of PIFs influencing performance integrally.

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