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Comparison between conventional and digital nuclear power plant main control rooms: A task complexity perspective, Part II: Detailed results and analysis

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A R T I C L E I N F O

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A B S T R A C T

Part II of this study aims to provide detailed, diagnostic information about the complexity difference between conventional and digital main control rooms (MCRs) in nuclear power plants. Complexity factors were classified according to task components and complexity dimensions. The effects of operator experience and plant type on complexity factors were statistically analyzed from three levels, i.e., task components, complexity dimensions, and individual factors. Interface management complexity factors were compared with other factors in digital MCRs. The results suggest that generally operator experience had effects on several task components and complexity dimensions only in abnormal/emergency situations. Plant type affected several task component and complexity dimensions in both abnormal/emergency and normal situations. Complexity factors in the affected task components and complexity dimensions had higher frequency, complexity, or impact in digital MCRs than those in conventional MCRs. Factors related to crew activity and the dimensions of overabundance, temporal demand, and variability had relatively high frequency, complexity, or impact. Compared with other factors, interface management complexity factors had marginally higher frequency, but significantly lower complexity and impact.

Relevance to industry: This study quantitatively addresses the complexity difference between conventional and digital MCRs in detail. It may provide rich information for how to improve operator working environments in NPPs. It may also contribute to other applied domains, such as human reliability analysis and interface design.

1. Introduction

In nuclear power plants (NPPs), the digitalization in main control rooms (MCRs) is mainly characterized by the widely usage of digital instrumentation and control systems (I&C) and automation. Fully digital and computerized I&C are deployed in new MCRs. In the conventional MCRs, they are also replacing analog, hardwired I&C systems in the control room modernization process. Automation systems cover all aspects of operator activities (e.g., plant monitoring, controlling, and decision-making) (O'Hara, 2005). Advanced human–system interface (HSI) systems are introduced, such as computerized procedure system, display system, alarm system, and operator decision support system (Roth and O'Hara, 2002). The main drive for digitalization in MCRs is to enhance safety and productivity.

In other complex safety-critical domains, such as aviation, digital technologies have been widely adopted. Their negative effects were well documented (e.g., Billings, 1997; Dekker and Woods, 1999). Quite a few studies (e.g., Sebok, 2000; Roth and O'Hara, 2002; Salo et al., 2006; Andersson and Osvalder, 2007) have been conducted to investigate the effects of digital technologies and compare the effects of MCR type on operators in NPPs. The effect of plant type (conventional vs. digital MCRs) on performance, workload and situation awareness was examined in a simulator by Sebok (2000). It was found that generally performance and workload were higher in digital MCRs than those in conventional MCRs, and situation awareness did not differ in both MCRs. In a conventional MCR modernization process, Roth and O'Hara (2002) studied the impact of introducing computerized HSI systems using interview and naturalistic observational methods. They reported that overall the introduction of computerized HIS positively impacted crew performance. It expanded the range of data available to the operators, increased flexibility, and reduced workload. Salo et al. (2006)

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interviewed operators in conventional power plants and NPPs and summarized that although the modernization process has showed some successes, it created new challenges for operators, such as increased requirements for competence, collaboration, and development of awareness of the process state. Andersson and Osvalder (2007) examined the effect of automatic and manual operations on operator performance in hybrid MCRs. They reported that task factors (e.g., time pressure and task criticality) influenced operator performance and workload more than automation level. They suggested that in manual operations operators have better situational understanding. The aforementioned studies have mixed results. Generally, there are still less operator field experience on the effects of digital technologies. Especially, there are no studies quantitatively describing the difference of operator experience in conventional and digital MCRs.

The digitalization in NPPs shapes operator cognition and working environments. Especially, complexity in working environments will be changed by the digitalization. The change will influence operator performance and reliability (Sasangohar and Cummings, 2010). This study is the first study to quantitatively compare the complexity between conventional and digital MCRs. It consists of two parts. Part I has presented the methodology, psychometric of quantitative methods, overall results and analysis of this study. Generally, it suggests that complexity factors in digital MCRs had higher frequency of occurrence, complexity, and impact than those in conventional MCRs.

In Part II, detailed results and analysis will be given to answer the question about the changes of complexity factors with digitalization. It will provide diagnostic information about the difference between conventional and digital MCRs. Based on the task complexity model (Liu and Li, 2012), it classifies the complexity factors following two ways. On one hand, factors are classified into different task components. On the other hand, factors are classified into different complexity dimensions. Thus, the effect of operator experience and plant type on the frequency, complexity, and impact of factors will be analyzed from task component, complexity dimension, and finally factor aspects. Several specific interface management complexity factors in digital MCRs will be involved.

2. Methods

As described in Part I, 69 licensed NPP operators participated in this study. Among them, there were 27 operators (19 junior and 8 senior operators) from conventional MCRs and 42 operators (32 junior and 10 senior operators) from digital MCRs. Junior operators were reactor operator, block manager, or deputy shit supervisory. Senior operators were unit supervisor or shift supervisor. This classification of operators was suggested by one NPP operational executive. A complexity factor in MCRs was quantified in terms of three aspects, i.e., its frequency of occurrence in MCRs, the complexity that the occurrence of the complexity factor brings to MCR tasks, and the impact caused by the factor to MCR tasks. Five-point Likert type scales were used to measure these three aspects. The five levels for frequency were "*never met*", "*seldom met*", "*sometimes met*", "*often met*", and "*always met*". For complexity, they were "*not complex*", "*sometimes complex*", "*moderately complex*", "*quite complex*", and "*very complex*". For impact, they were "*no impact*", "*slight impact*", "*moderate impact*", "*high impact*", and "*very high impact*". The five levels in frequency, complexity, or impact were quantified from 0 to 4. Items (i.e., factors) in the complexity questionnaire (see the Appendix in Part I) were from several related studies (i.e., Vicente and Burns, 1995; Braarud, 1998, 2000; Collier, 1998; O'Hara et al., 2002; Gertman et al., 2005; Bye et al., 2010; Sasangohar and Cummings, 2010; Liu and Li, 2012). The complexity questionnaire was evaluated in two conditions, abnormal/emergency and normal situations. In abnormal/emergency situations the number of complexity factors was 77 and in normal situations, it was 34. The reliability (i.e., Cronbach's alpha and Spearman-Brown split-half reliability) and validity (i.e., construct validity and criterion validity) were found to be acceptable.

Liu and Li (2012) suggested a task complexity framework to identify complexity factors. In their framework, a task has six components, i.e. input, process, output, goal, time, and presentation. Ten definitional complexity dimensions are summarized, i.e. size, variety, ambiguity, relationship, variability, unreliability, novelty, incongruity, action complexity, and temporal demand. A task sometimes is referred to "a complex situation capable of eliciting goal directed behavior" (Farina and Wheaton, 1971, p. 10). The complexity framework described by Liu and Li (2012) can be used in working situations such as MCRs. The combination of task components and complexity dimensions produces a cross-table shown in Table 1 in which each cell presents one type of complexity factors. Thus, this cross-table can be used to generate, elicit, and organize complexity factors. For example, the size of input can be a general complexity factor. In MCRs, input can be information sources (e.g., indicators, displays, panels, alarms, crew members, logs, shift turnover, etc.), faults, procedures, interruptions, etc. Process can be information acquisition and detection, information analysis, decision and diagnosis, and action implementation. Time can be time demands and time availability. Presentation can be physical human–computer interfaces, such as displays and panels. The difference between input and presentation is that the former focuses on content and the latter on physical carrier. Output and goal are not considered for the present study.

The task complexity framework was used to organize the complexity factors surveyed in this study. Some modifications have been made. First, the output and goal components were not involved because no complexity factors are related to the two components in the current study. Second, the process component was decomposed into five information processing activities, information acquisition, information analysis, decision and selection, action implementation, and crew activity. The former four activities come from Parasuraman et al. (2000). These four activities are usually referred to individual activities. Another sub-component, crew activity (e.g., team coordination and cooperation), was added to organize crew behaviors. Third, the size dimension was decomposed into two sub-dimensions, deficiency and overabundance. Deficiency means too few, such as lack of information. Overabundance describes too much, such as information overload. Three researchers independently classified complexity factors according to the task complexity framework for this study. Their results were summarized and finally reached consensus. The results are shown in Table 1.

We analyzed the effects of operator experience and plant type on complexity factors from three aspects, i.e. task components, complexity dimensions, and individual complexity factors. Regarding the aspect of task components, complexity factors in the same component were averaged. A series of univariate ANOVA analysis were conducted to examine the effects of operator experience and plant type on the five components (input, information acquisition, information analysis, action implementation, and crew activity), in terms of the frequency, complexity, and impact of complexity factors belonging to them. Other three components (decision and selection, time, and presentation) were not involved, because there are only one or two factors belonging to the three components. In normal situations, only two factors are related to information analysis. Thus, information analysis was not involved in normal situations. Regarding the level of complexity dimensions, complexity factors in the same dimension were averaged. The