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Reliability forecasting for operators' situation assessment in digital nuclear power plant main control room based on dynamic network model

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ABSTRACT

With the technical development of computer hardware and software, digitalization is a trend in large-scale complex systems such as nuclear power plants (NPPs). It changes the way main control room (MCR) operators interact with systems. Faced with these technical changes, operators need to continue improving their situation assessment (SA) reliability level. In addition to evaluate operators' SA reliability, managers and shift supervisors also want to forecast their SA reliability level. There have been many studies with respect to operators' SA, but most of them are static analysis method and cannot be applied to predict operators' SA reliability. So, on the basis of different forecasting approaches and observation data, how to predict the operators' SA reliability level has became a problem that many analyst interest in. In this paper, first we identified the influence factors associated with SA reliability, and then we developed the SA reliability model, finally we proposed a reliability forecasting model by integrating time series forecasting method with dynamic network model (DNM). Our experiment verification focused on steam generator tube rupture (SGTR) event, using the forecasting model, we demonstrated how to predict operators' SA reliability during the course, and the prediction results are consistent with measurement results.

1. Introduction

With the technical development of computer hardware and software, digitalization is a trend in large-scale complex systems such as nuclear power plants (NPPs). The human–machine system of the main control room (MCR) change from analog to digital, this change require higher requirement for operators' reliability. Many studies (Gu et al., 2012; Zhang et al., 2010a; Zhou et al., 2012) have shown that the adoption of digital technology has brought some new risks for MCR operators, for example, important information are not observed in time because of "keyhole effect"; important alarm signals shielded by operators; interface management tasks are increasing due to the "enormous information with limited display areas"; additional cognitive load and working load are brought to operators, which increased the chance of human errors occurred, such as loss of situation awareness and mode confusion. All of these are more likely to lead to errors of omission (EOOs). Whether the reliability of these technologies can meet the safety and economic requirements has become one of the urgent problems that NPPs must solve.

Compared with conventional main control room, the digital MCR has dramatically changed the whole operating environment, and the ways operators interact with the plant systems (Zhou et al., 2012). Operators have changed their role in the total system from the manual controllers to the supervisor of automated system (Kim and Seong, 2001). In the digital MCR, operators' primary tasks have changed from operation to monitoring and decision-making, the cognitive characteristics of tasks is increasing. That is because many changes have taken place in the operational behavior, the ways of human–system interaction and the cognitive environment which the operators in (Zhou, 2012; Zhou et al., 2013). According to NUREG-6634 (O'hare et al., 2000b), the operators' primary tasks involve several generic cognitive tasks; i.e., monitoring and detection, situation assessment (SA), response planning, and response implementation. In these cognitive tasks, SA plays an important role in the whole operation process, because it not only determines the reliability of the subsequent response planning, but also affects

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the operators' monitoring (Zhang et al., 2010a). The reliability of operators' SA reflects their identification and comprehension for the current status of NPP; it directly determines the effectiveness of operator's interventions and plant safety. Incorrect SA will not only lead to an accident, and also will make a further deterioration. Human error which caused by incorrect SA is one of the most important factors to many serious accidents (Endsley, 2000; Nullmeyer et al., 2005). Three Mile Island (TMI) accident can be proved this point.

Bayesian Network (BN) also known as belief network, which is a modeling method belong to the artificial intelligence. One of main applications of BN is as an inference engine for calculation the probability of an event given the observation of other events. BN has now been used to construct assessment model for the operators' SA in the NPP (Dai et al., 2012; Li, 2011; Kin and Seong, 2006; Zhou et al., 2012; Zhou, 2012). Although operators' SA model which based on BN can be well described the correlation between operators' SA reliability and its influencing factors, but due to the static characteristics of belief network, quantification results of these models are lack of dynamic, cannot reflect the dynamic process of operators' SA with the development of the incident in the time series. If we can have a dynamic model for predicting the reliability of operators' SA, that will provide a theoretical basis for shift supervisors and managers to make assessment for operator's performance.

High performing NPPs employ analytic tools and techniques to continuously improve their forecasts, predict and manage risk. In order to really predict operators' SA reliability, forecasting models have to be used. There are two types of forecasting approaches can be used, one is causal model and the other is time series forecasting method (Sander de Bree, http://www.exsyn.com). Any forecasting models depend on two main criteria: cause–effect analyses and historical data. Dagum et al. (1992) developed a probabilistic forecasting methodology through a synthesis of belief network models and classical time series analysis, and presented the dynamic network model (DNM). The DNM representation can extends static belief network models to more general dynamic forecasting models. Utilizing this method, in this paper we first identify the influence factors associated with operators' SA reliability and construct the reliability model for SA, then on the basis of reliability model, combined with time series forecasting method, DNM which used for predict the operators' SA reliability can be established.

In Section 2, we discuss the basic concepts of the SA, influence factors associated with SA reliability and correlation between these factors. In Section 3, we introduce definitions and properties of the DNM, and propose the reliability forecasting model. In Section 4, we present procedures for predicting the reliability of operators' SA. In Section 5, we give an example from the experimental study. We conclude with a discussion of the advantages of this method, and some problems that remain to be solved.

2. Reliability model of situation assessment

When faced with an abnormal occurrence, operators actively try to construct a coherent, logical explanation to account for their observations. This cognitive activity, situation assessment, is the evaluation of current conditions to determine that they are acceptable or to determine the underlying causes of abnormalities when they occur (O'hare et al., 2000a, 2008). SA is a dynamic cognitive process, operators need to identify the changes of system operating status by integrating the information they observed with their general knowledge; then make assessment for the current system status by analyzing the changes of state parameters of NPP, and providing decision basis for the subsequent response planning. SA is performed repeatedly with the evolution of system status, its reliability level play a vital role for the safety running.

In this paper we present that the reliability level of SA involves three related concepts: the operators' mental level, the systems' status level and the operators' stress level. The operators' mental level is built up through formal education, system-specific training, and operational experience. The systems' status level consists of technical level of systems and components, such as human–machine interface and system automation level. The operators' stress level includes such influence factors: available time, quality of procedures, and system complexity.

Here we considering the operators' stress level as a bridge which interact with the operators' mental level and the systems' status level (for example, if available time inadequate and tasks complexity high, that the operators' stress level will inevitably increase; meanwhile high stress can also affect the operators' mental level), in order to reflect the relationship of operators' SA reliability between two adjacent time nodes in the time-series, we determine the operators' stress level as intermediate variables, which connect the operators' mental level and the systems' status level. Fig. 1 is the operators' SA reliability model.

In order to forecasting the operators' SA reliability, refer to THERP and SPAR-H methods (Swain and Guttmann, 1983; Gertman et al., 2005), we determine seven influence factors associated with the reliability model and assign each factor three level, detailed descriptions seen in Table 1 and the model structure seen in Fig. 2. The operators' mental level contains crew cooperation and communication, training two factors; the operators' stress level contains procedures, available time and system complexity three factors; the systems' status level contains human–machine interface and system automation level two factors.

3. Reliability forecasting model based on DNM

A dynamic network model can be constructed from a set of building blocks which are static belief network (as shown in Fig. 1), together with a set of temporal dependencies that capture the dynamic behavior of variables (Armbruster and Carlsson, 2011). To avoid the progressive deterioration of the model, the forecasting model must update the conditional probabilities and structure when new evidence arrives. In our work, we extend the reliability model to a reliability forecasting model (as shown in Fig. 3) by introducing relevant temporal dependencies between representations of the static network at different times (Dagum et al., 1992).

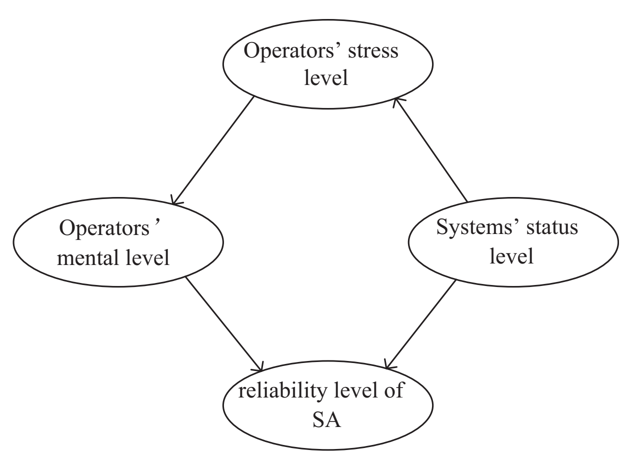

Fig. 1. Operators' SA reliability model.