Safety Science 80 (2015) 296–300

Contents lists available at ScienceDirect

Safety Science

journal homepage: www.elsevier.com/locate/ssci

Study on dynamic evolution of operators' behavior in digital nuclear power plant main control room – Part I: Qualitative analysis

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ARTICLE INFO

Article history:
Received 17 January 2015
Received in revised form 25 June 2015
Accepted 30 July 2015
Available online 24 August 2015

Keywords:
Digital main control room
Dynamic evolution
Operators' behavior
Boolean network
Human reliability analysis
Semi-tensor product

ABSTRACT

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. Many studies shows that the adoption of digital technology has brought some new risks for MCR operators, and whether the reliability of these technologies can meet safety and economic requirements has become one of the urgent problems that NPPs must solve. The study consists of two parts. In Part I, we investigated the dynamic evolution of operators' four behaviors: monitoring and detection (MD), situation assessment (SA), response planning (RP), and response implementation (RI). This paper incorporates Boolean network (BN) analysis into the field of human reliability analysis (HRA), by applying semi-tensor product of matrix (STP), whereby the dynamics evolution of operators' behavior can be expressed in an algebraic form. Utilizing this algebraic representation, a BN analysis model is proposed, on which we based a qualitative analysis. An illustrative example is given to show how to construct the BN model via experimental data. We also discuss the advantage of the proposed methodology, its feasibility and highlighting the future work remaining.

1. Introduction

In recent years, nuclear reactors under construction and planned in China began adopting digital control systems (DCSs), such as Generation II (e.g., CNP-600), II+ (e.g., CRP-100), and III reactors (e.g., AP1000) (World Nuclear Association, 2013). In addition, some conventional nuclear power plants (NPPs) in China are upgrading their analogy instrumental & control (I&C) systems in main control rooms (MCR), for example, replacing their paper-based emergency operating procedures (EOPs) with computerized ones (Liu and Li, 2014a). Quite a few studies have been conducted to investigate the effects of digital technologies (Liu and Li, 2014b) and their impacts on operator performance in the MCR (Zhou et al., 2012). Since DCSs were adopted in NPPs, operators have been enjoying the conveniences they provide; at the same time, they have also been facing operational reliability risks caused by enormous amounts of centralized information. In the digital MCR, the central display of system alarms, parameters and pictures has formed a "keyhole effect" with enormous information available and limited display areas (Gu et al., 2012; Zhang et al., 2010). Operators in a conventional MCR can easily get information from the control panel; while in the digital MCR, they have to use a video display unit (VDU) to perform interface management tasks to find information promptly and efficiently (O'Hare et al., 2000b). These studies have shown that the adoption of digital technology has brought some new risks for MCR operators, and whether the reliability of these technologies can meet the safety and economic requirements has become one of the urgent problems that NPPs must solve.

With technological advances in reactor design, human-system interface (HSI) design and control system, MCR personnel play a more important role in the safety. Inappropriate operator behaviors can be important contributors to the risk. In carrying out their roles and responsibilities, digital MCR operators perform two types of tasks: primary tasks and secondary tasks. Primary tasks have a number of common cognitive elements. These common elements are referred to as generic primary tasks. They are monitoring and detection (MD), situation assessment (SA), response planning (RP), and response implementation (RI) (O'Hare et al., 2008). When addressing operators' behavior, these tasks are discussed rather than the detailed specific tasks they perform, such as starting pumps and monitoring steam flow (O'Hare et al., 2000a). In this paper, we analyze these four tasks as operators' behavior, because they play a vital role in operators' cognitive process.

There have been many studies on these four behaviors respectively (Gertman et al., 2005; Jiang et al., 2011; Zhou et al., 2013),

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http://dx.doi.org/10.1016/j.ssci.2015.07.033

but no one consider them as a whole. Neither has anyone conducted an overall analysis of the logical relationship and dynamic evolution of these four behaviors. Event tree analysis methodology (ET) has been widely used for analyzing operators' behavior in human reliability analysis (HRA) (NRC, 1975), it can describe the evolutionary process of behaviors, but in every branch point of the tree it only can represent one behavior at a time. The dynamic event tree (DET) methodology, designed to treat the integrated behavior of process variables (Acosta and Siu, 1993), can analyze several behaviors simultaneously, but the model structure is complex and cannot model the evolutionary process of behaviors in mathematical form. These two methods are based on boolean logic, which suggests that other analysis methods based on boolean logic may help us understand the logical evolution of operators' behavior. If we can propose a method for modeling the dynamic evolution of operators' behavior, it will contribute to existing HRA methods.

After an initiating event, the operators' response behaviors change with the process of an accident: operators' behavior at the next time node is closely related to the state of the plant system and the operations which the operator performed at this current time node. This dynamic evolution in fact is logical process, so it can be well described by boolean networks (BN) (Dipl.Phys.Florian Greil, 2009), which is a powerful tool in system control. To achieve this purpose, this paper proposes an approach: by applying a new matrix calculation method, called semi-tensor product of matrix (STP) (Cheng et al., 2011; Cheng and Qi, 2007), in which BN equations are represented by general discrete-time equations, combined with experimental data collected through simulator experiments and video analysis. A BN model can be constructed to analyze the dynamic evolution of operator's MD, SA, RP, and RI behaviors.

In Section 2, we discuss the structure of BN. In Section 3, we introduce some definitions and properties of STP. In Section 4, we present an example to show how to construct the BN model and address the qualitative analysis. We conclude with a discussion of the advantages of the BN approach, its feasibility and highlighting the future work remaining.

2. Boolean networks

Boolean network was firstly introduced by Kaufman to formulate the cell networks (Kauffman, 1969). It became a powerful tool in describing, analyzing, and simulating the cell networks, and has also been used to model some complex systems such as neural networks. A BN is a particular kind of sequential dynamical system, where time and states are discrete, i.e., both the set of variables and the set of states in the time series each have a bijection onto an integer series. It is a directed network graph, consists of a set of nodes, and a set of edges.

A BN is a set of nodes $x_1, x_2, \dots, x_n$, which interact with each other in a synchronous manner. At each given time $t = 0, 1, 2, \dots$ a node has only one of two different values: 1 or 0. Thus the network can be described by a set of equations:

$$\begin{cases} x_1(t+1) = f_1(x_1(t), \dots, x_n(t)) \\ x_2(t+1) = f_2(x_1(t), \dots, x_n(t)) \\ \qquad\qquad \cdots \\ x_n(t+1) = f_n(x_1(t), \dots, x_n(t)) \end{cases} \tag{1}$$

where $f_i : D^n \to D,\ i = 1, \dots, n$ are n-ary logical functions, $x_i(t) \in D$ are state variables.

From the model structure, the value of state variables at time $t + 1$ related to a logical function and values of state variables at time t, which means this model can establish the logical relationship for these state variables between two adjacent time points. Utilizing this characteristic, in this paper, operator's MD, SA, RP, and RI behaviors are represented as state variables $x_i(t)$, we try to find the logical functions $f_i (i = 1, 2, 3, 4)$ and then BN model can be constructed, which could describe the dynamic evolution process of operators' behaviors. Before this we need to introduce some basic knowledge about STP, because it is very important for modeling.

3. Definitions and proposition of STP

In this section, we only introduce the main definitions and propositions of STP which will be used in derivation and calculation in the following sections. More detailed refer to (Cheng and Qi, 2007).

I. Definition (*1*). (i) Let $X = [x_1, \dots, x_s]$ be a row vector, $Y = [y_1, \dots, y_t]^T$ be a column vector.

①: If $s = t \times n$. Then

$$\langle X, Y\rangle_L := \sum_{k=1}^{t} X^k y_k \in \mathbb{R}^n \tag{2}$$

where $X = [X^1, \dots, X^t],\ X^i \in \mathbb{R}^n,\ i = 1, \dots, t$. We call $\langle X, Y\rangle_L$ a STP.

②: If $t = s \times n$. Then

$$\langle X, Y\rangle_L := (\langle Y^T, X^T\rangle_L)^T \in \mathbb{R}^n \tag{3}$$

$\langle X, Y\rangle_L$ also called a STP.

(ii) Assume $M \in M_{m\times n},\ N \in M_{p\times q}$, if n is the divisor of p or p is the divisor of n. We call $C = M \ltimes N$ is the semi-tensor product of M and N.

If C is composed of $m \times q$ blocks, $C = (C^{ij})$, meanwhile

$$C^{ij} = \langle M^i, N_j\rangle_L,\ i = 1, \dots, m,\ j = 1, \dots, q. \tag{4}$$

where M^i is a row of M, N_j is a column of N.

Throughout this paper, the matrix product is assumed to be the STP. In the following, the symbol $\ltimes$ is omitted.

II. Proposition (*1*). (i) If $A \in M_{m\times np},\ B \in M_{p\times q}$. Then

$$A \ltimes B = A(B \otimes I_n). \tag{5}$$

(ii) If $A \in M_{m\times n},\ B \in M_{np\times q}$. Then

$$A \ltimes B = (A \otimes I_p)B. \tag{6}$$

Proposition (*2*). Let $X \in R^m,\ Y \in R^n$ be two columns. Then

$$W_{[m,n]} \ltimes X \ltimes Y = Y \ltimes X; \tag{7}$$

$$W_{[n,m]} \ltimes Y \ltimes X = X \ltimes Y. \tag{8}$$

where $W_{[m,n]}$ is a $mn \times mn$ matrix, called the swap matrix.

Proposition (*3*). Let $x \in \Delta$. Then

$$x^2 = M_r x \tag{9}$$

where $M_r = \delta_4[1, 4]$ is called the power-reducing matrix.

III. Definition (*2*). Let σ be an r-ary logical operator. $M_\sigma \in M_{2\times 2^r}$ is called the structure matrix of σ, if in the vector form we have

$$\sigma(p_1, \dots p_r) = M_\sigma \ltimes p_1 \ltimes p_2 \ltimes \dots \ltimes p_r = M_\sigma p_1 \dots p_r \tag{10}$$

Theorem (*1*). Assume $f(x_1, \dots, x_n)$ is a logical function, and in the vector form we have $f : \Delta_{2^n} \to \Delta$. Then there exists a unique logical matrix M_f, called the structure matrix of f, such that following Eq. (11) holds.

$$f(x_1, \dots, x_n) = M_f x. \tag{11}$$

where $x = \ltimes_{i=1}^{n} x_i$.