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Dependence assessment in human reliability analysis using an evidential network approach extended by belief rules and uncertainty measures

Xinyang Deng *, Wen Jiang *

School of Electronics and Information, Northwestern Polytechnical University, Xi'an 710072, China

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ABSTRACT

Because of the potential relevance among human errors, dependence assessment for human actions plays a very important role in human reliability analysis. Several typical methods have been developed for that task. However, in previous studies various uncertainties in analyst's judgment and expert's knowledge for dependence assessment is not fully taken into consideration, especially the epistemic uncertainty in expert's knowledge is often ignored. In this paper, a belief function theory is employed to simultaneously model the probabilistic uncertainty and epistemic uncertainty within analyst's judgment and expert's knowledge. Mainly, a novel evidential network approach extended by belief rules and uncertainty measures is proposed, then based on that a new framework for dependence assessment is presented and its effectiveness is validated through an illustrative case study. This work, on one hand, gives an extended evidential network model on the basis of belief rules and uncertainty measures to implement dimension reduction and uncertainty reasoning; On the other hand, it presents a novel and effective framework for dependence assessment in human reliability analysis.

1. Introduction

As a crucial ingredient in the probabilistic safety assessment (PAS) of a large-scale complicated system, human reliability analysis (HRA) aims to quantify human's contribution to the system risk for a given task so as to provide valuable suggestions in improving the reliability for that task (Hendrickson, 2015; Swain and Guttmann, 1983; Park, 2014; Zou et al., 2017). A number of HRA techniques have been developed and used in a variety of industries (Ekanem et al., 2016; Akyuz and Celik, 2015; Hu et al., 2018; Alvarenga et al., 2014). In general, HRA is a process of evaluating human's performance and associated impacts on structures, system, and components for a complex facility Čepin (2008a). Among them, dependence assessment is a key issue in HRA, which aims to assess the influence of failure of an operator to perform one task on the failure probabilities of subsequent tasks (Zheng and Deng, 2018; Swain and Guttmann, 1983; Whaley, 2012; Blackman and Boring, 2017).

The research of dependence assessment in HRA has attracted people's attention for a long time, and many methods have been developed in last decades. The technique for human error rate prediction (THERP) (Swain and Guttmann, 1983; Boring, 2012) is a representative and still widely used method. In THERP, some influential factors, for example "spatial relatedness", "functional relatedness", and others, are suggested for providing guidelines, and five levels of dependence including zero dependence (ZD), low dependence (LD), moderate dependence (MD), high dependence (HD), and complete dependence (CD), are given for evaluating the dependence between two tasks according to the suggested factors. Moreover, THERP gives a uniform formula to calculate the conditional human error probability (CHEP) given the failure probability of a preceding task. However, although THERP is simple and easily used, it has still received some criticism since the obtained result may lack traceability and repeatability (Podofillini et al., 2010a).

To overcome the deficiencies of THERP, a model called decision trees (DTs) has been imported in the field of dependence assessment in HRA (Podofillini et al., 2010b). Several typical methods are Standardized Plant Analysis Risk-Human Reliability Analysis (SPAR-H) (Gertman et al., 2005), DEPEND-HRA (Čepin, 2008b), Institute Jožef Stefan human reliability analysis (IJS-HRA) (Čepin, 2008c), and so on. In these methods, the model of DTs provides convenience for representing the relationships between input factors and dependence levels to reduce the judgemental input. However, the construction of DTs often lacks a transparent expert elicitation process, which may lead to the difficulty of tracing the

* Corresponding authors.
E-mail addresses: xinyang.deng@nwpu.edu.cn (X. Deng), jiangwen@nwpu.edu.cn (W. Jiang).

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fundamental hypotheses behind the relationships (Zio et al., 2009). In order to improve the flexibility of the representation of analyst's judgment and the transparency of the expert elicitation process, a fuzzy expert system (FES) based HRA method (Podofillini et al., 2010a; Zio et al., 2009) has been proposed. In the FES method for HRA, the analyst judgment involving uncertainty is represented by fuzzy linguistic variables, and the relationships between different input factors are modelled by fuzzy rules as well.

By summarizing the development of methods for dependence assessment in HRA, two main issues have been given the most attention. One is the way to represent the uncertainty in the analyst's judgment. Probabilities, fuzzy numbers are common used (Swain and Guttmann, 1983; Podofillini et al., 2010a; Zio et al., 2009), and belief function theory (Dempster, 1967; Shafer, 1976) is also employed recently to express the uncertainty and imprecision in analyst's judgment (Su et al., 2015; Guo et al., 2017; Musharraf et al., 2013), and D numbers as well (Deng and Jiang, 2017; Deng and Deng, 2018). The other is the tool to represent the expert's knowledge about the input factors and the relationships between these input factors for dependence assessment. Apart from representative DTs and FES mentioned above, Bayesian belief networks (BBNs) (Groth and Swiler, 2013; Mkrtchyan et al., 2015) and analytic hierarchy process (AHP) (Su et al., 2014; De Ambroggi and Trucco, 2011; Chen et al., 2017) also become popular tools in recent years. Especially in the aspect of uncertainty representation, since there exists human being's judgment, it inevitably involves various types of uncertainties which are not only probabilistic uncertainty caused by randomness but also epistemic uncertainty resulted from limited knowledge. In previous studies, they mainly considered the uncertainty contained in the analyst's judgment, the uncertainty in expert's knowledge about the relationships between input factors for dependence assessment, however, is not well addressed. For example, in Su et al. (2015), Guo et al. (2017), Chen et al. (2017) belief function theory is only used to express the uncertainty in the analyst's judgment. And in the FES method (Podofillini et al., 2010a; Zio et al., 2009) although the fuzziness is involved by using fuzzy rules, the missing information and ignorance are still not taken into consideration.

To overcome the limitation that the epistemic uncertainty is not well considered in many methods for dependence assessment, this paper employs belief function theory (Dempster, 1967; Shafer, 1976) to simultaneously represent the probabilistic uncertainty and epistemic uncertainty in analyst's judgment to every input factor and in expert's knowledge about the relationships between input factors. At first, we extend an evidential network approach proposed by Simon and Weber (2009), Simon et al. (2008) by using belief rules to express the limited knowledge having epistemic uncertainty. The new evidential network is called ENwBRs, which can better represent expert's knowledge on the relationships between input factors in dependence assessment. And an inference algorithm for the ENwBRs is also developed based on the uncertainty measures in belief function theory. Then, on the basis of the ENwBRs approach, a new framework for dependence assessment in HRA is presented, which fully considers the probabilistic uncertainty and epistemic uncertainty in the process of dependence assessment. At last, a case study is given to demonstrate the effectiveness of the proposed ENwBRs based method for dependence assessment. By summarizing this work, the contribution of the study is twofold. At first, the original evidential network is improved to a new network with belief rules on the basis of the idea of dimension reduction, and an inference algorithm for this novel evidential network is developed to implement the uncertainty reasoning based on an uncertainty measure for BPAs. At second, in terms of the improved evidential network approach a novel and effective framework is presented for dependence assessment in human reliability analysis, which provides a new solution for this issue.

The rest of the paper is organized as follows. Section 2 gives some brief introductions about belief function theory, uncertainty measures in that theory, and evidential network approach. Then, a novel evidential network approach extended by belief rules and uncertainty measures is proposed to improved the original evidential network approach in Section 3. Section 4 gives a new framework for dependence assessment based on the novel evidential network approach, and the effectiveness of the presented framework is validated in Section 5. At last, Section 6 concludes this paper.

2. Preliminaries

2.1. Basics of belief function theory

Belief function theory (Dempster, 1967; Shafer, 1976), which is also called Dempster-Shafer theory or evidence theory, is an effective tool to deal with uncertain information (Denoeux, 2013; Han et al., 2016; Jiang et al., 2017a, 2018a; Sadiq et al., 2007; Bolar et al., 2013), and it is widely used in decision making (Yager and Alajlan, 2016; Deng and Jiang, 2018; Jiang and Wei, 2018; Xiao, 2018), classification and clustering (Denoeux et al., 2016; Xu et al., 2017; Jiang et al., 2018b; Xu and Deng, 2018; Liu et al., 2016), failure mode and effects analysis (Liu et al., 2013a,b; Jiang et al., 2017b; Gong et al., 2018; Xiao, 2017), and so on. In belief function theory, a frame of discernment (FOD) is a set of mutually exclusive and collectively exhaustive events denoted by $\Theta = \{\theta_1, \theta_2, \cdots, \theta_n\}$. The power set of Θ is denoted as 2^Θ.

Definition 1. [BPA] Given a FOD, a mapping $m : 2^\Theta \rightarrow [0, 1]$ is a mass function, which is also called a basic probability assignment (BPA), defined on Θ if it satisfies

$$m(\emptyset) = 0 \quad \text{and} \quad \sum_{A \subseteq \Theta} m(A) = 1. \tag{1}$$

If $m(A) > 0$, then A is called a focal element, and the union of all focal elements is called the core of a BPA.

In belief function theory, $m(A)$ measures the belief assigned exactly to A and it represents how strongly the evidence supports A. The belief measure Bel and plausibility measure Pl associated with a BPA express the lower bound and upper bound of the support degree for each proposition in a BPA, respectively. They are defined as

$$Bel(A) = \sum_{B \subseteq A} m(B), \tag{2}$$

$$Pl(A) = 1 - Bel(\bar{A}) = \sum_{B \cap A \neq \emptyset} m(B), \tag{3}$$

where $\bar{A} = \Omega - A$. Obviously, $Pl(A) \geqslant Bel(A)$ for each $A \subseteq \Theta$, and $[Bel(A), Pl(A)]$ is called the belief interval of A.

In belief function theory, two independent BPAs can be combined by Dempster's rule of combination denoted by $m = m_1 \oplus m_2$:

$$m(A) = \begin{cases} \frac{1}{1-K} \sum_{B \cap C = A} m_1(B) m_2(C), & A \neq \emptyset; \\ 0, & A = \emptyset. \end{cases} \tag{4}$$

with

$$K = \sum_{B \cap C = \emptyset} m_1(B) m_2(C), \tag{5}$$