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Review

Bayesian belief networks for human reliability analysis: A review of applications and gaps

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ABSTRACT

The use of Bayesian Belief Networks (BBNs) in risk analysis (and in particular Human Reliability Analysis, HRA) is fostered by a number of features, attractive in fields with shortage of data and consequent reliance on subjective judgments: the intuitive graphical representation, the possibility of combining diverse sources of information, the use the probabilistic framework to characterize uncertainties. In HRA, BBN applications are steadily increasing, each emphasizing a different BBN feature or a different HRA aspect to improve. This paper aims at a critical review of these features as well as at suggesting research needs. Five groups of BBN applications are analysed: modelling of organizational factors, analysis of the relationships among failure influencing factors, BBN-based extensions of existing HRA methods, dependency assessment among human failure events, assessment of situation awareness. Further, the paper analyses the process for building BBNs and in particular how expert judgment is used in the assessment of the BBN conditional probability distributions. The gaps identified in the review suggest the need for establishing more systematic frameworks to integrate the different sources of information relevant for HRA (cognitive models, empirical data, and expert judgment) and to investigate algorithms to avoid elicitation of many relationships via expert judgment.

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1. Introduction

Human reliability analysis (HRA) aims at systematically identifying and analysing the causes, consequences and contributions of human failures in socio-technical systems (e.g., nuclear power plants, aerospace systems, air traffic control operations, chemical and oil and gas facilities). For many industrial sectors, with differences in the level of sophistication and detail of the applications and methods, HRA is an established practice within the Probabilistic Safety Assessment (PSA) (or Probabilistic Risk Assessment, Quantitative Risk Assessment, Formal Risk Assessment as it may be referred to, depending on the industrial sector). HRA is an essential element for using PSA for regulatory and operational decisions.

A number of HRA methods are used in the current practice [1–7]. They differ in their scope, the types and levels of decomposition of the tasks addressed, and the factors considered to influence the error probability. The methods guide analysts in the identification of potential human errors, in the analysis of the performance contexts and in the quantification of error probabilities. Despite the established and successful practice, there are some areas of HRA in need of development, among these: extensions of the method scope (to different types of errors and to other industrial sectors); stronger basis on cognitive models and empirical data; applicability to advanced human-machine interfaces; more structured and detailed qualitative analyses, and more empirically-based representation of the failure influencing factors. For comprehensive and recent analyses of the strengths and limitations of HRA methods, see [8–10].

Recently, applications of Bayesian Belief Networks (BBNs) to HRA are receiving increasing attention. Generally speaking, BBNs appear promising for their ability to represent complex influencing factor relationships. Also, their ability to combine different sources of information potentially allows developing HRA models with a stronger basis on cognitive theory and empirical data. BBNs are models that represent and quantify probabilistic relationships among factors. Their primary use is the representation of knowledge and decision support under uncertainty; their application is established in diverse areas such as medical diagnosis and prognosis, engineering, finance, information technology, natural sciences [11–15]. Their use ranges from data-mining applications to the representation of expert knowledge in rare-event applications; the latter situation being typical of risk analysis. The general use of BBNs in data-rich applications is to identify the important factors, their relationships (correlations and causal relationships) and their quantitative influence on the variables of interest, as these emerge from the data. In most of the applications dealing with rare events, BBNs are used to represents the expert knowledge about factors and their influences.

HRA is a field in which data is scarce, but precious. Bayesian frameworks have been naturally recognized as appropriate methods for handling scarce, multi-source data, potentially allowing to improve both the estimation of human error probabilities and the underlying assumptions in the quantitative algorithms employed by the different HRA methods [16]. Correspondingly, BBN applications in HRA have steadily increased within the last decade. The studies using BBNs within the HRA domain can be grouped as follows [17]. A number of studies use the BBN ability to the model multi-level influences of Management and Organizational Factors (MOF) on human error [18–28]. In some cases [19–20] these studies have extended previous safety analyses by mapping/integrating traditional reliability models such as fault trees to BBNs, in an effort to integrate the BBN ability to model soft influences (e.g. from human or more generally organizational factors) within existing safety models. BBNs have been used to understand and capture the relationships among PFSs and the quantitative impact of PSFs configurations on the error probability [29–34]. Some contributions proposed BBN versions of existing HRA models, such as SPAR-H and CREAM [35–37], by introducing additional modelling features such as interdependent Performance Shaping Factors (PSFs)[1] [35] and extending the deterministic approach of the control mode assessment in CREAM [36]. BBN applications to improve dependency assessment in HRA are presented in [38–41]. Potential misdiagnosis errors by nuclear power plant operators are analysed exploiting BBN backward reasoning, i.e. reasoning from effects to possible causes [42–44]. The use of BBNs for HRA has found applications within different industries: nuclear [18,29,30,35,36,38,39,42–44], oil industry [19–24,28,34,37], and aviation [26,27,30].

Each of the mentioned studies emphasizes a different BBN feature relevant for HRA: e.g. ability to deal with scarce data, to incorporate diverse information, to model complex multi-layer relationships. The present paper systematically surveys these applications, critically reviewing these features as well as identifying research needs. Five groups of HRA applications are identified [17]: modelling of organizational factors, analysis of the relationships among PSFs, BBN-based extensions of existing HRA methods, dependence assessment among Human Failure events (HFEs), and modelling of situation assessment. The present paper analyses in further detail the contributions from each group. The review gives special emphasis to how the BBNs are built and in particular to how expert judgment is incorporated into the models. Indeed, given the limited availability of empirical data for comprehensive model validation, the phase of model development acquires special importance for the acceptance of the models. Also, generally, for HRA applications, the primary source of information when developing BBN models is expert judgment – though important exceptions are [29,30]. The present paper analyses the approaches used to elicit the expert knowledge, to include it into the BBN model and to combine this expert data with empirical data, when available. Note that a very important area of on-going development for HRA is the collection of data from simulated environment: fundamental issues are being researched and tools and guidelines are being developed, e.g. [45–48]. On the one hand, it can be expected that these efforts will enhance the empirical basis of HRA models and, eventually, decrease the requirement for judgment for some HRA applications. On the other hand, the elicitation of expert knowledge will maintain key importance for HRA, especially for applications for which data will be very difficult to obtain. This is the case, for nuclear PSA applications, of HRA for accident mitigation conditions and external initiating events, as examples. Also, expert judgment will remain an important source of information for industrial sectors in which the collection of HRA data is less advanced than in the nuclear industry.

The paper is organized as follows. Section 2 briefly presents BBNs. In Section 3, the HRA aspects modelled by BBNs are presented and each of the five HRA application groups is discussed in detail. Section 4 addresses the BBN development process in the reviewed

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[1] In the present paper these factors will be generically referred to as Performance Shaping Factors (PSFs), as they are often referred to in HRA – although some HRA methods refer to these factors differently to highlight their different features.