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Comparing the treatment of uncertainty in Bayesian networks and fuzzy expert systems used for a human reliability analysis application

Piero Baraldi [a,*], Luca Podofillini [b], Lusine Mkrtchyan [b], Enrico Zio [a,c], Vinh N. Dang [b]

[a] Energy Department, Polytechnic of Milan, Milan, Italy
[b] Paul Scherrer Institute, PSI Villigen, Switzerland
[c] Chair on Systems Science and the Energetic Challenge, Fondation EDF, École Centrale Paris and Supélec, Paris, France

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ABSTRACT

The use of expert systems can be helpful to improve the transparency and repeatability of assessments in areas of risk analysis with limited data available. In this field, human reliability analysis (HRA) is no exception, and, in particular, dependence analysis is an HRA task strongly based on analyst judgement. The analysis of dependence among Human Failure Events refers to the assessment of the effect of an earlier human failure on the probability of the subsequent ones. This paper analyses and compares two expert systems, based on Bayesian Belief Networks and Fuzzy Logic (a Fuzzy Expert System, FES), respectively. The comparison shows that a BBN approach should be preferred in all the cases characterized by quantifiable uncertainty in the input (i.e. when probability distributions can be assigned to describe the input parameters uncertainty), since it provides a satisfactory representation of the uncertainty and its output is directly interpretable for use within PSA. On the other hand, in cases characterized by very limited knowledge, an analyst may feel constrained by the probabilistic framework, which requires assigning probability distributions for describing uncertainty. In these cases, the FES seems to lead to a more transparent representation of the input and output uncertainty.
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1. Introduction

Handling of different sorts of uncertainties is intrinsic to risk analysis and, correspondingly, many publications have addressed the issue since decades [1–4]. The probabilistic and Bayesian frameworks are since long the established practice to represent and quantify uncertainty in risk analysis and, in particular, in Probabilistic Safety Assessment (PSA) [5–7]. Recently, alternative, non-probabilistic frameworks (e.g. Fuzzy Logic, possibility theory, imprecise probability) have also been increasingly proposed and investigated to represent uncertainty in situations characterized by limited available information, mainly coming from expert judgements [8–13]. However, these frameworks have not yet found visible application outside the scientific community. Some reasons for this are: (*i*) the probabilistic framework is strongly embedded in the whole risk assessment process (e.g. in the risk practitioner mindset, which is "probabilistic", in the interpretation and use of results for risk-informed decision-making and, generally, regulatory decisions); (*ii*) the perceived lack of empirical foundation of some concepts behind non-probabilistic frameworks [14,15]; (*iii*) the difficulty for practitioners to understand (or the failure of the scientific community to communicate) the differences in the mathematical frameworks and their implications in the analysis results [16]. An exhaustive treatment of these issues is beyond the scope of the present paper: refer to [8,17] for a comprehensive treatment.

In this context, the present paper takes a practitioner standpoint and compares two frameworks for supporting assessments relevant for risk applications, Bayesian Belief Networks (BBNs) and Fuzzy Expert Systems (FESs), on a specific, very important, issue for Human Reliability Assessment (HRA), namely dependence analysis. Comparison of probabilistic and non-probabilistic frameworks is not a new endeavour and has been addressed in several works, e.g. [8,9,11,17,18]. However, in most cases, the comparison is made at the theoretical level of the mathematical frameworks, which makes its understanding difficult outside, for example Bayesian or Fuzzy Logic experts. The emphasis of the present paper on the application problem is helpful to disseminating, with practical perspective, the understanding of the differences within the risk analysis community.

The application of interest for this paper relates to HRA, the part of PSA analyzing Human Failure Events (HFEs), in terms of the

* Corresponding author. Tel.: +39223996355; fax: +39223996309.
E-mail address: piero.baraldi@polimi.it (P. Baraldi).

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factors contributing to the failure, and quantifying their probabilities, referred to as the Human Error Probabilities (HEPs). Ideally, the models used to derive these probabilities should be built and validated on empirical data—e.g. from operational experience or studies in simulated environments. Examples of this use of data can be found in [19]. However, the challenges in data collection efforts (mostly related to the collection of data related to decision or diagnosis tasks) are such that in the newest HRA methods (ATHEANA [20], MERMOS [21], CESA [22,23], MDTA [24]), the source of quantification is mostly expert judgment.

Within HRA, a task that is particularly founded on expert judgment (and highly subjective) is the assessment of the dependence among HFEs. Dependence analysis aims at evaluating the influence of an operator failure in performing one task on the performance of the subsequent task. Intuitively, if two tasks are "closely related" in some fashion and the operators have failed the first task, the failure of the second task may be assessed as more likely than following the success of the first task. From a quantitative point of view, the dependence assessment results in the Conditional Human Error Probability (CHEP), on the basis of the identification of the conditioning influencing factors and the quantification of their impact on the HEP. The dependence assessment may have a significant impact on the risk profile of the system, because the dependent/conditional failure probability may be orders of magnitude larger than the unconditional one.

In current HRA practice, the evaluation of dependence is typically performed through the elicitation of a qualitative dependence level: the Technique for Human Error Rate Prediction (THERP) [25] provides some guidelines for the assessment and also includes formulas for modifying the CHEP according to the dependence level. The direct use of expert judgment to assess the qualitative dependence level has a number of weaknesses, including the traceability and repeatability of the results. In some cases, simplified approaches such as decision trees are used; however the rules represented by these trees do not have a transparent basis [26,27].

A structured alternative is that the evaluation is performed by an analyst, who assesses the conditions of the situation under study through the use of expert systems, i.e. mathematical models which mimic the experts' evaluation. This way of proceeding should make the evaluation more systematic and repeatable and increase the traceability of the results. Two such expert systems based on Fuzzy Logic (FL) and Bayesian Belief Network (BBN) theory have been previously investigated by the authors, in [28,29], respectively. For the purpose of demonstration, the dependence model underlying the two expert systems has been kept simple and it is by no means exhaustive in the inclusion of the factors that may influence the dependence among operator actions in practice.

The goal of this work is to present an in-depth comparison of the two expert system approaches to dependence assessment, based on their application to exemplary case studies. In particular, the focus is on the uncertainty treatment and representation in all the evaluation steps to investigate:

- how the analyst may translate his/her assessment of the situational conditions into suitable input to the expert system for the dependence assessment;
- how uncertainties propagate to the outcome of the dependence assessment;
- how the uncertainty in the dependence outcome is represented.

The scope of the comparison is on the mathematical treatment and representation of uncertainty. Some aspects of a full scope comparison have been left out, most notably, those related to the construction of the two models. In particular, to focus on the mathematical differences, the two models are maintained relatively similar, maintaining a correspondence between the FL linguistic labels and the BBN states and between the fuzzy rules and the Conditional Probability Tables (CPTs) of BBN. A full scope comparison would entail addressing the definition of the linguistic labels and of the BBN states as well as the determination of the Fuzzy rules and BBN CPTs from data, expert elicitation or a combination of the two.

Section 2 briefly outlines the two expert system models previously developed for the dependence assessment; Section 3 describes in details how the uncertainty in the input assessment is handled by the two models and highlights the practical differences. Section 4 focuses on the outcomes of the dependence assessment. Then, in Section 5 the two models are applied to a number of case studies to see how the uncertainties in the input assessment propagate to the output. Conclusions are finally drawn in Section 6.

2. Expert systems for human error dependence assessment

Two HFEs are said to be dependent if the probability of failure of one task changes depending on the success or failure of the other. Since sufficient data are typically not available, the relevant conditional probabilities are qualitatively inferred from the nature of the tasks involved and from human factors considerations. For example, the THERP method [25] proposes guiding principles asserting an increasing level, or degree, of dependence between two tasks if:

- the two tasks are close in time;
- the two tasks share systems and functions;
- the performers of the tasks have similar characteristics.

A discussion of the limitations of current approaches for human error dependence treatment is beyond the scope of the present paper (see [27] for more details). The idea behind the work in [28,29] is to build a computable model that represents the relationships among the relevant factors (for the present application, relevant to the dependence between two events) and between these factors and the HEP. The potential benefits from the use of expert models in HRA (connected with possible increased transparency and repeatability of HRA analysis) have been discussed by the authors of the present paper in [27].

The use of expert systems for HRA dependence assessment here is demonstrated on a working model proposed in [27,28] that builds on the qualitative rules suggested in THERP. The model does not include all factors that may impact the dependence level, but is deemed of enough complexity for the purposes of this demonstration.

The inputs to the model are: "Closeness in Time", "Task Relatedness" and "Similarity of Performers". "Task Relatedness" is then specified in terms of the "Similarity of Cues" and "Similarity of Goals" (Fig. 1). In the subsequent text, the labels of the input and output variables are shortened and referred as "Time", "Task" and "Performers". "Task" is then specified in terms of the "Cues" and "Goals", respectively.

2.1. The FES for human error dependence assessment

The first expert system considered for the dependence assessment relies on the FL framework [30]. While conventional Boolean logic deals with the concepts which are either true or false, FL models the concepts of partial truth by introducing membership functions (MF). FL has been applied in many decision-making problems and proved to be a promising tool to handle uncertainty, ambiguity, imprecision and vagueness which are inevitable characteristics for many real-life problems [31–33].

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