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A comparison between a probability bounds analysis and a subjective probability approach to express epistemic uncertainties in a risk assessment context – A simple illustrative example

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A B S T R A C T

A common approach to reliability and risk assessments is based on using probability models to reflect aleatory uncertainties (i.e. variation in large populations of similar units) and using subjective probabilities to describe epistemic uncertainties about the unknown parameters of the probability models. The use of subjective probabilities for this purpose has, however, been subject to strong criticism: it is argued that the approach provides too precise results when relating these to the information available. The assignments are based on a number of assumptions and proper justification for many of these seems to be lacking. Several alternative approaches have been suggested to meet this critique, including probability bounds analysis (PBA). The purpose of this paper is to compare a PBA with a subjective probability analysis, based on different types of information, covering varying levels and quality of hard data and expert judgments. A simple production assurance example is used to illustrate the differences. The comparison highlights the dependence on assumptions with different levels of justification. The analysis performed also constitutes an illustration of a two-step approach, where a subjective probability approach is followed and accompanied by a PBA approach and where the result of both assessments are presented to the decision-maker.

1. Introduction

Challenges related to and research into the treatment of epistemic uncertainty has been given substantial attention by the risk assessment community for several decades. A major initiative in this respect was the so-called epistemic uncertainty workshop organized by Sandia National Laboratories in Albuquerque, New Mexico, USA, in 2002. Several works arising from this workshop were published in a special issue of the journal Reliability Engineering & System Safety; see the guest editorial by Helton and Oberkampf [17] for an introduction and overview. The special issue articles focus on the applicability and usefulness of some of the recent approaches suggested for treating epistemic uncertainty in risk assessments. In particular, Oberkampf et al. [23, p. 11] specify two challenge problems focused on “the representation, aggregation, and propagation of epistemic uncertainty and mixtures of epistemic and aleatory uncertainty through two simple model systems”. The challenge problems are “a simple algebraic system of the form $y = (a + b)^a$” and “a simple dynamic system of the form of an initial value problem given by an linear ordinary differential equation” (Oberkampf et al. [23], p. 15). Other articles in the special issue approach and handle these problems using different types of mathematical representations of epistemic uncertainty.

The use of unjustified probability distributions is a key criticism raised against the subjective probability approach; see e.g. Ferson and Ginzburg [14], Ferson et al. [15] and Aven and Zio [4]. The argument is that the use of such probabilities is often based on unjustified assumptions and that the available knowledge is not sufficiently strong to justify the use of specific probability distributions. A subjective probability approach requires a probabilistic structure to be placed on the set of possible values of the uncertain quantity (or quantities) of interest, e.g. on an uncertain observable quantity or on a set of uncertain model parameters. For example, suppose that the size of a gas cloud (in m^3) in the case of a gas leak will be somewhere in the interval [0, b], considering that the relevant process plant segment at most can contain hydrocarbons corresponding to b m^3 of gas at the ambient temperature and pressure. There is no further information available regarding the size of gas cloud that would support statements such as that a gas cloud size of c m^3 is more, less or equally likely than a gas cloud size of d m^3, $0 \leq c, d \leq b$. The risk analyst may then assign a uniform distribution on [0, b] to express the uncertainty related to the size of the gas cloud. The analyst is then implicitly stating, for example, that a cloud size some-

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where in the interval [0, b/2] is equally likely as a cloud size in the interval [b/2, b], without having any particular justification for doing so. The assignment of such a probability distribution (although not necessarily this particular assignment) is required if a subjective probability approach is to be used.

One specific alternative approach that has been proposed to deal with the type of problem described above is probability bounds analysis (PBA); see e.g. Ferson and Ginzburg [14], Tucker and Ferson [27], Ferson and Tucker [13], Beer et al. [7] and Sentz and Ferson [24]. Ferson and Tucker [13] present PBA as a marriage between probability theory and interval analysis, and highlight potential benefits of using PBA. For example, they point to the ability of PBA to ([13], p. 1436): “comprehensively account for possible deviations in assessment results arising from uncertainty about

- distribution parameters,
- distribution shape or family,
- intervariable dependence, and even
- model structure.”

Another argument raised by Ferson et al. [15] is the potential for removing the commonly used but often unjustified assumption of independence. The ability of PBA to avoid the independence assumption and also to perform calculations without assuming specific probability distributions, exemplifies how PBA requires fewer and less informative assumptions - but having stronger justification – than the traditional probabilistic approach [15]. The potential for simple yet useful analysis is highlighted by Ferson and Tucker [13]. The argument is that simple and crude intervals often are sufficient to support decisions, for example when the whole resulting interval is either above or below a specific risk acceptance limit. On the other hand, a concern when using PBA is that the resulting intervals can be extremely wide, meaning that they do not provide very informative decision support; thereby requiring further studies, including sensitivity analysis. This issue relates to the two concerns, as discussed by Aven and Zio [4, p. 69], that need to be balanced, namely that:

I. “*the knowledge should to the extent possible be “inter-subjective” in the sense that the representation corresponds to documented and approved information and knowledge and*
II. *the risk analysts’ judgments (degrees of belief) should be clearly reflected.*”

In the present paper, we investigate and illustrate differences between a PBA approach and a more traditional subjective probability founded analysis when applied to a simple production assurance example. Although the example is simple, it is still realistic and interesting from a practical decision oriented perspective. Compared to the challenge problems from the epistemic uncertainty workshop, the example studied in the present paper is specific on both the decision-making context of the risk assessment as well as on how the input information used is obtained. Special emphasis is placed on assumptions made as part of the analysis, including their (level of) justification.

For a general risk assessment, a set of different ways of producing the input are available to an analyst, including:

1) Constraints (e.g. positive lifetimes and restoration times, and probabilistic inequalities).
2) Hard data (on e.g. production volumes, lifetimes and restoration times).
3) Modelling of the system performance (e.g. of the availability of the system).
4) Bayesian updating.
5) Aggregation (fusion) (combining data from several sources).
6) Judgments (degrees of belief of unknown quantities).

In the paper, we study how the different types of input (mainly 2, 3 and 6) are reflected in the risk assessments and in particular the way risk is reported and communicated to support the decision-making. The purpose of the present paper is not to apply the currently most sophisticated methods of analyzing the case within each approach. Rather, the purpose is to highlight the dependence on assumptions associated with different levels of justification when applying the basic principles of both types of approaches.

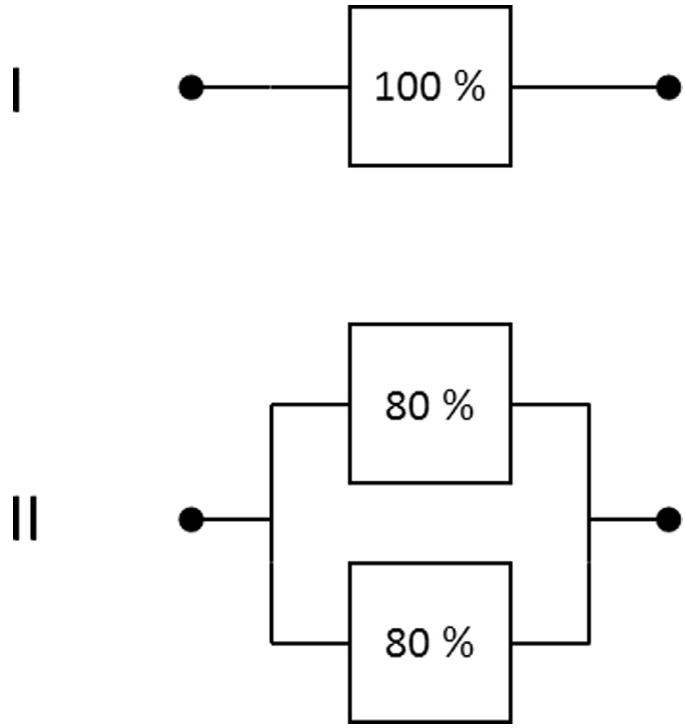

Fig. 1. The two design alternatives considered.

Similar types of work comparing different approaches for quantitatively representing epistemic uncertainties has been carried out, in particular, the publications stemming from the epistemic uncertainty workshop described above. Efforts beyond the workshop include Beer et al. [8], Bernardini and Tonon [9], Karanki et al. [19], Baraldi and Zio [6] and Flage et al. [16].

The paper is organized as follows. In Section 2, the case study is introduced. Then, in Section 3, we outline the main features of an assessment of this case using a subjective probability approach. Focus is on the representation and treatment of the different types of inputs. Some of the key theoretical pillars of this approach – including interpretations – are reviewed in Appendix A1; we also refer to textbooks on Bayesian statistics such as Bernardo and Smith [10], Congdon [12] and Iversen [18]. Section 4 has an analogous structure but with the PBA replacing the subjective probability analysis. A brief introduction to probability bounds analysis can be found in Appendix A2; see also the references given in the third paragraph of the present section. Section 5 compares and discusses the assessments carried out in Sections 3 and 4. Finally, Section 6 provides some conclusions.

2. Case description

A gas producing company (the operator) is considering two design alternatives (I and II) for a new production facility, see Fig. 1. Alternative II represents the base case; it consists of two parallel processing trains, each one having a capacity of 80% compared to the overall throughput demand. Alternative I consists of one train only, rated at 100% capacity.

The operator intends to use the system to produce gas and distribute it to its customers. The present analysis is, however, restricted to the gas production system only. The decision-maker is the operator. A key concern for the operator is its reputation as a reliable gas producer. Other key concerns include health, safety and environmental (HES)