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Some reflections on uncertainty analysis and management

Terje Aven

University of Stavanger, Norway

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ABSTRACT

A guide to quantitative uncertainty analysis and management in industry has recently been issued. The guide provides an overall framework for uncertainty modelling and characterisations, using probabilities but also other uncertainty representations (including the Dempster–Shafer theory). A number of practical applications showing how to use the framework are presented. The guide is considered as an important contribution to the field, but there is a potential for improvements. These relate mainly to the scientific basis and clarification of critical issues, for example, concerning the meaning of a probability and the concept of model uncertainty. A reformulation of the framework is suggested using probabilities as the only representation of uncertainty. Several simple examples are included to motivate and explain the basic ideas of the modified framework.

1. Introduction

A guide to uncertainty analysis and management in industry has recently been issued [8]. The guide is written by a project group of the European Safety, Reliability and Data Association (ESReDA). The book project is motivated by the fact that no authorative standard exists for how to analyse and quantify uncertainty. The guide presents a numbers of practical cases, all based on the same uncertainty analysis framework (see Fig. 1).

The key variables of interest are denoted Z (which could be a vector). To assess Z a model $G(X,d)$ is introduced, which links a set of input variables X and some fixed quantities d to Z (also X and d could be vectors). To describe the uncertainties, probabilistic and non-probabilistic methods can be used. A common approach is to use a parametric probability distribution (where μ is the parameter) to establish a probability distribution for X. Using the model G, an uncertainty description is obtained for Z. The tool used for this purpose could be an analytical approach or Monte Carlo simulation. Some quantities of interest, for example, expected values and variances, are specified and computed from the measure of uncertainty derived, typically the probability distribution of Z. These quantities provide input to a decision process, which could be based on some decision criteria expressing, for example, that a probability should not exceed a specified level. Sensitivity analysis provides insights about how the input quantities affect the output quantities, and importance ranking identifies what factors, subsystems, etc. are the most important based on some defined criteria, for example, the contribution to the variance. The result of the analysis may lead to some action (feedback process), for example, that there is a need for design changes to meet the criteria. The actions need to be seen in relation to the goals of the analysis, which usually fall into the following categories:

Understand: To understand the influence or rank the importance of uncertainties, and thereby to guide any additional measurement, modelling or research and development efforts.

Accredit: To give credit to a model or a method of measurement, i.e. to reach an acceptable quality level for its use. This may involve calibrating sensors, estimating the parameters of the model inputs, simplifying the system model physics or structure, fixing some model inputs, and finally validating according to a context-dependent level.

Select: To compare relative performance and optimize the choice of maintenance policy, operation or design of the system.

Most analysts and researchers would probably consider this framework a logical and useful structure for performing uncertainty analysis in practice. There is not much controversial or problematic about the framework described at this overall level. However, when we go into the details, the meaning and use of the different concepts are not so straightforward. There are many challenges, and in this paper we will look closer into some of these including:

1. The way of representing uncertainties and, in particular, the importance of clarifying the meaning of the representations.
2. Model uncertainty, its meaning and relevance.

These issues are discussed in the coming section. We argue that if the analysis is restricted to a probabilistic representation of uncertainty, all the probabilities in Fig. 1 need to be knowledge-based (subjective) probabilities. If relative frequency-interpreted

E-mail address: terje.aven@uis.no

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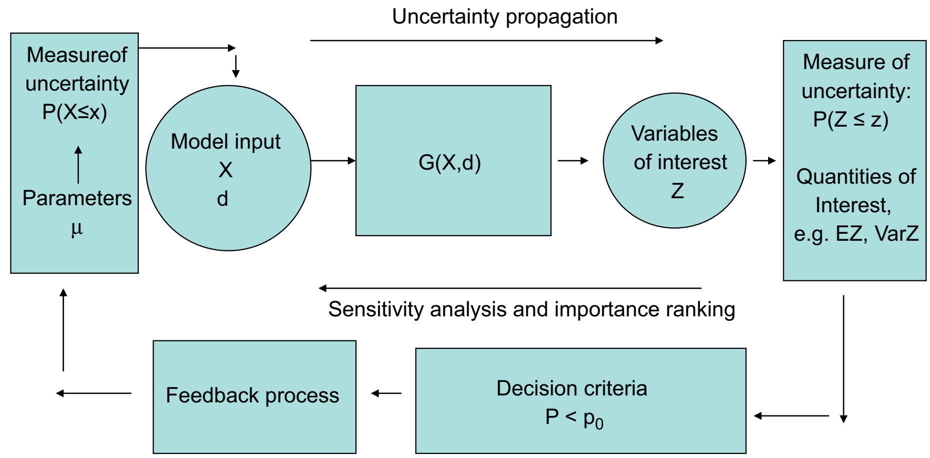

Fig. 1. The overall framework adopted by the uncertainty analysis guide [8].

probabilities (chances) are introduced, they need to be considered as model input variables *X* or variables of interest *Z*. This observation makes it possible to simplify the framework, its understanding, presentation and use. Section 3 presents a revised framework according to these observations. Section 4 provides some final remarks and conclusions.

The present paper has a focus on the use of probability to measure uncertainty, although the de Rocquigny et al. [8] framework allows for both probabilistic and non-probabilistic representations of uncertainty. Of the non-probabilistic representations, the Dempster–Shafer theory is given special attention in the guide. We refer to Flage et al. [11] for a discussion of the use of this theory in the context of uncertainty and risk analysis (see also Section 2.2).

The de Rocquigny et al. [8] framework is the starting point for the reflections made in this paper. However, our analysis extends beyond this particular guide. The issues addressed are general and relates to fundamental topics in uncertainty analysis and management.

2. Discussion of some of the key features of the analysis framework

We will address the following issues:

- overall structure and link to risk assessment,
- understanding and use of the probability concept,
- model uncertainty,
- decision-making context.

2.1. Overall structure and link to risk assessment

The basic structure of the framework resembles other frameworks used for analysing uncertainties and risk. An example is the approach for risk assessment recommended by Aven [2] (see Fig. 2).

Fig. 2 is read as follows: A risk analyst (risk analyst team) conducts risk analysis. Focus is on the future performance of the system (the world), and in particular some quantities reflecting the performance of the system *Y* (could be a vector). Based on the analyst's understanding of the world, the analyst develops a model (several models), that relates the overall system performance measure *Y* to *X*, which is a vector of quantities on a more

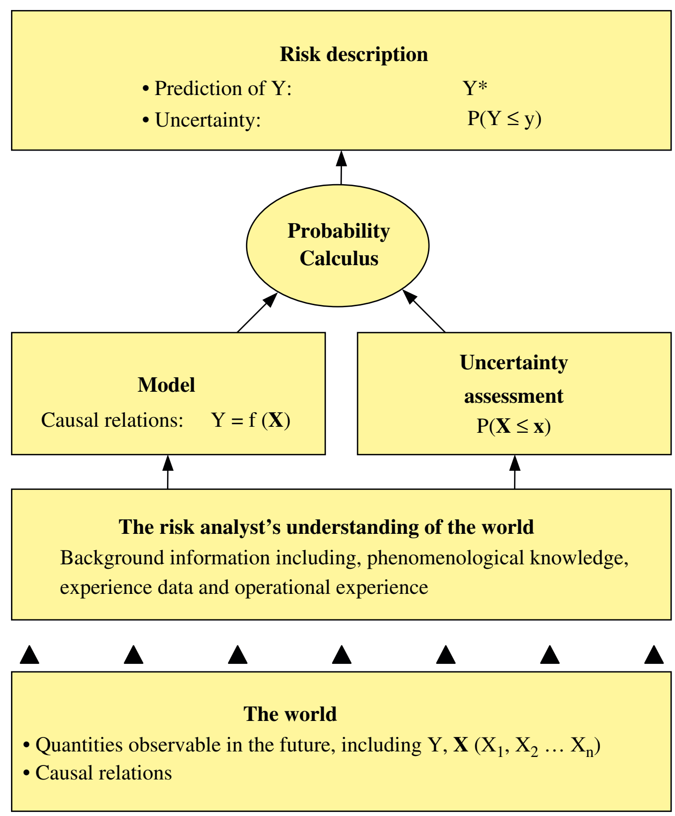

Fig. 2. The structure of the risk assessment according to the analysis approach recommended by Aven [2].

detailed level. The analyst assesses uncertainties of *X*, and that could mean the need for simplifications in the assessments, for example, using independence between component states *X*. Using probability calculus, the uncertainty assessments of *X* together with the model *f*, gives the results of the analysis, i.e. the assigned probability distribution of *Y*, and a prediction of *Y*.

Uncertainty is a main component of risk in this setting. Formally, risk is defined as the two-dimensional combination of the consequences (expressed by *Y*) and the associated uncertainties (*U*) [3,6]. Hence, the uncertainty analysis constitutes an integral aspect of the risk analysis. However, other risk perspectives exist where the uncertainty analysis is not a natural part of the risk analysis. Many risk analyses produce risk estimates of unknown parameters without addressing uncertainties in the estimates and