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Combined analysis of unique and repetitive events in quantitative risk assessment

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ABSTRACT

For risk assessment to be a relevant tool in the study of any type of system or activity, it needs to be based on a framework that allows for jointly analyzing both unique and repetitive events. Separately, unique events may be handled by predictive probability assignments on the events, and repetitive events with unknown/uncertain frequencies are typically handled by the probability of frequency (or Bayesian) approach. Regardless of the nature of the events involved, there may be a problem with imprecision in the probability assignments. Several uncertainty representations with the interpretation of lower and upper probability have been developed for reflecting such imprecision. In particular, several methods exist for jointly propagating precise and imprecise probabilistic input in the probability of frequency setting. In the present position paper we outline a framework for the combined analysis of unique and repetitive events in quantitative risk assessment using both precise and imprecise probability. In particular, we extend an existing method for jointly propagating probabilistic and possibilistic input by relaxing the assumption that all events involved have frequentist probabilities; instead we assume that frequentist probabilities may be introduced for some but not all events involved, i.e. some events are assumed to be unique and require predictive – possibly imprecise – probabilistic assignments, i.e. subjective probability assignments on the unique events without introducing underlying frequentist probabilities for these. A numerical example related to environmental risk assessment of the drilling of an oil well is included to illustrate the application of the resulting method.

1. Introduction

The Kaplan and Garrick [30] approach for describing risk has for several decades served as a cornerstone to the field of quantitative engineering risk assessment. According to this approach, risk is equal to and expressed by the set of triplets consisting of (accident) scenarios, the likelihoods λ of these scenarios and their consequences. Three likelihood settings are mentioned by Kaplan [29]: repetitive situation with known frequency ($\lambda = f$, where f is a frequentist probability), unique situation ($\lambda = p$, where p is a subjective probability), and repetitive situation with unknown frequency ($\lambda = H(f)$, where H is a subjective probability distribution on the unit interval of frequencies). The last mentioned setting is typically

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dealt with using the so-called probability of frequency approach, wherein knowledge about all potentially occurring events involved is assumed to be represented by uncertain frequentist probabilities of occurrence, and the epistemic uncertainties about the true values of the frequentist probabilities are described using subjective (also referred to as judgmental or knowledge-based) probabilities. Of course, the first case above is a special case of the third.

A repetitive event is an event whose occurrence or not can be embedded into a hypothetically infinite sequence of similar situations (technically: an exchangeable sequence), whereas a unique event cannot because such a sequence cannot reasonably be envisaged. As an example of a repeatable event, consider the tossing of a die. We can envisage tossing the die over and over again under similar conditions, thus generating a limiting frequency of the event that the die shows '1' (say). On the other hand, as an example of a unique event, consider the case of a particular election for choosing the president of a country. We cannot reasonably envisage a hypothetically infinite number of repetitions of this particular election, because among other issues, candidates are not all the same from one election to the other. Hence, we cannot introduce a frequentist probability of some candidate winning, but we rather just directly assign a predictive subjective probability of this event. Determining whether to treat an event as repeatable or unique is often a judgement call by the analyst; we refer to Section 7 for a discussion of this issue.

As another example, consider an oil and gas company performing an environmental risk assessment of the activity drilling a wildcat oil well. If there is oil at the drilling location, some might be inclined to argue that a number of factors (such as the physical characteristics of the reservoir, e.g. the reservoir pressure at a particular point in space and time; and the performance of technical barrier systems, e.g. whether a particular barrier element functions on demand) come into play to generate a frequentist probability of an oil spill due to a blowout or well-leak (since the reservoir pressure at a particular point in space changes over time, and the barrier element is not perfectly reliable). On the other hand, if there is no oil present in the reservoir, the frequentist probability of a blowout of oil is zero. Oil or no oil is a fixed but unknown state of the world – it is not subject to randomness. The situation cannot be repeated such that in some cases there is oil in this particular reservoir, while in others there is not.

As a final example, to the extent that Probabilistic Risk Assessment (PRA) is suitable for terrorism risk, a terrorist attack is also a unique event. It is however not a fixed but as-yet-unrevealed event, like presence of oil in the environmental risk assessment example. Yet a relative frequentist probability of a terrorist attack cannot be meaningfully defined [7].

The quantitative risk assessment setting can be formally summarized as follows: We are interested in a quantity Z (possibly a vector) and introduce a model $g(X)$ with input quantities $X = (X_1, X_2, \dots, X_n)$ to predict Z. The quantities Z and X could be the total number and a vector of the number of fatalities due to different accident scenarios, respectively. Alternatively, for a particular explosion accident scenario, Z and X could be the explosion pressure and a set of factors (quantities) affecting the explosion pressure, respectively. Or Z could be an indicator quantity for some overall event of interest, e.g. blowout in an offshore Quantitative Risk Assessment (QRA) setting or meltdown in a nuclear QRA/PRA setting, and X could be a set of indicator quantities for events that, through various combinations, could lead to the occurrence of the overall event, respectively.

In the present paper we focus on the last setting. Hence, for our purpose Z and X are 0–1-valued unknown quantities where Z equals 1 if some high level event A takes place and 0 otherwise, i.e. $Z = I(A)$. Corresponding to $X = (X_1, X_2, \dots, X_n)$ are the lower level events $B = (B_1, B_2, \dots, B_n)$, in the sense that $X_i = I(B_i)$, $i = 1, 2, \dots, n$, where I is the indicator function equal to 1 if its argument is true and 0 otherwise. This is a setting commonly dealt with using basic risk analysis models such as fault trees (comprising top events and basic events) and event trees (comprising initiating events, branching events and end events).

In the probability of frequency approach one would by default introduce a frequentist probability f of the event A, and a set of frequentist probabilities $q = (q_1, q_2, \dots, q_n)$ of the basic events B according to the structure of an event model g. A frequentist probability expresses the fraction of times the event of interest occurs when repeating the situation considered over and over again infinitely. The setting then yields $f = g(q)$, and by establishing a subjective probability distribution over the vector q and propagating it through the model g, a probability distribution of the frequency probability f is established. Particular attention might then be put on the expected value of f, which is assumed to be also the predictive probability of A, i.e. $E[f] = P(A)$.

In the present paper, following Kaplan and Garrick [30], we relax the assumption that frequentist probabilities of occurrence can be defined for all events involved. Instead we consider a setting where frequentist probabilities can be defined for some but not all events involved – some events are assumed to be unique and their uncertainty can only be assessed using predictive subjective probability assignments, or more generally, as will be argued, as imprecise probabilities.

The main contribution of the present paper is the formulation of a set-up for the combined analysis of unique and repetitive events in quantitative risk assessment that extends the Kaplan and Garrick [30] methodology to a setting allowing for imprecise probabilities, that either represent epistemic uncertainty on frequentist probabilities, or represent expert uncertainty concerning unique events. The imprecise probability approach has been argued to be a more faithful representation of partial information than unique distributions. As a particular case, the paper describes the extension, to the joint presence of unique and repetitive events, of an existing method for jointly propagating probabilistic and possibilistic inputs to be applicable in such a setting. So this paper contributes to a better understanding of how to articulate the joint presence of aleatory and epistemic uncertainty in risk assessment.

Table 1 positions the present paper and its suggested methods in relation to existing frameworks and methods. The Bayesian framework (e.g. [10]) with its precise probabilities is straightforward to apply to settings involving respectively