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Decision Support

Risk analysis and decision theory: A bridge

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ABSTRACT

The risk-triplet approach pioneered by Kaplan and Garrick is the keystone of operational risk analysis. We perform a sharp embedding of the elements of this framework into the one of formal decision theory, which is mainly concerned with the methodological and modeling issues of decision making. The aim of this exercise is twofold: on the one hand, it gives operational risk analysis a direct access to the rich toolbox that decision theory has developed, in the last decades, in order to deal with complex layers of uncertainty; on the other, it exposes decision theory to the challenges of operational risk analysis, thus providing it with broader scope and new stimuli.

1. Introduction

The creation of quantitative tools for decision support is central in operations research and the management sciences. Decision support is often intertwined with a risk analysis or is a part of a decision analysis, with applications ranging from operational risk management in finance (Zhao & Huchzermeier, 2015), to supply chain risk assessment (Fahimnia, Tang, Davarzani, & Sarkis, 2015; Heckmann, Comes, & Nickel, 2015; Klibi & Martel, 2012), to the risk and reliability analysis of complex technological systems (Aven, 2016; Di Maio, Baronchelli, & Zio, 2014). At the same time, the analysis and modeling of decisions has become pivotal in a number of diverse fields such as social sciences, cognitive sciences, artificial intelligence, engineering, law, and medical sciences. Yet, their languages and methodologies are often very field specific. This impairs possible synergies among alternative disciplines and hinders the interdisciplinary transfer of ideas and techniques. Conversely, the interaction of fields and the exchange of methods from one to the other has often led to major developments. In this respect, several researchers are advocating the integration of the many disciplines involved in the theories and applications of risk analysis (Aven, 2016; Aven & Zio, 2014).

A first step in this direction requires bridging the language of risk analysis with that of decision theory.[1] We believe that this bridge is of interest for the risk management scientist as well as for the decision theorist. A first reward of such a link is to allow a close integration of the risk management part of decision analysis to the output of risk assessment. In fact, the degree of sophistication of the latter, in terms of detail in the quantification of uncertainty and modeling of scenarios, could allow for the use of more advanced decision making criteria than the ones typically adopted. A second, and related, reward is the possibility to account not only for attitudes toward uncertainty, which fundamentally characterize economic rationality, but also for other behavioral traits (e.g., loss aversion), in the optimality criteria used to select among risk management options. These considerations are normatively and descriptively desirable in applications (Aven & Zio, 2014; Paté-Cornell, 2007). As a recent example of an opening of risk analysis in this direction, Cox (2012) reviews several methods for risk analysis under deep uncertainty[2] borrowing from several fields, among which the management sciences and decision theory. Both fields are in fact increasingly sophisticated in dealing with criteria for decision making under uncertainty – see Soyster (1973),

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[1] Like most of risk researchers and analysts, here we intend risk analysis to be used as decision support, in the sense that its results inform the decision makers who then make decisions based on their preferences. In turn, the study of preferences, their properties, and their numerical representations is the main subject of decision theory.

[2] Deep (or severe) uncertainties are *"uncertainties about the state of the world and the human factors for which we know absolutely nothing about probability distributions and little more about the possible outcomes."* (Verbatim from Quade & Carter, 1989, p. 160).

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Bertsimas and Sim (2004), Bandi and Bertsimas (2014), Ben-Tal, Ghaoui, and Nemirovski (2009), Nemirovski (2012), and Shapiro, Tekaya, Soares, and da Costa (2013) for works in operations research and Gilboa and Marinacci (2013) and Marinacci (2015) for reviews of the decision theory perspective. Yet, a formal link between criteria developed in decision theory and the outcomes of a probabilistic risk assessment has not been developed so far. Building such a link is one of the purposes of the present work. Specifically, our goal is to provide a clear way to feed the output of a risk analysis into recently developed decision criteria.

This is not the first paper looking at the formal relation between risk analysis, risk management, decision analysis, and decision theory. In this respect, two relevant references are Paté-Cornell and Dillon (2006) and Paté-Cornell (2007). The focus in such works is, however, on the similarities of their formal structures in the expected utility frameworks of von Neumann–Morgenstern and Savage and on the differences in the roles of the agents involved and in their objectives (Paté-Cornell, 2007, p. 239).

Still, while it is true that the formal structures of risk analysis and decision theory are similar in the mentioned expected utility frameworks, if one wishes to consider more detailed descriptions of the involved uncertainties and more sophisticated decision criteria, the formal correspondence between the above structures is not trivial anymore. For example, under the expected utility theory assumptions, the distinction between epistemic and aleatory uncertainty,[3] when both uncertainties are modeled through probabilities, becomes irrelevant because of the possibility to reduce to the mean probability, when computing the optimal course of action, without affecting the decision outcome. However, this reduction is no longer irrelevant under more general assumptions accounting, for example, for different attitudes towards different sources of uncertainty (Cappelli, Cerreia-Vioglio, Maccheroni, Marinacci and Minardi, 2017; Chew & Sagi, 2008; Ergin & Gul, 2009; Nau, 2006) or recurrent cognitive biases (Kahneman, 2011). Moreover, the use of such synthesis could be seen as inadvisable from both a normative and a descriptive viewpoint, in that it produces a significant loss of relevant information on the nature of the involved uncertainties, an issue already raised by Paté-Cornell (2007).

Our primary contribution and the main important difference relative to the above mentioned works is to make a translation that allows risk analysts to seamlessly access more general decision theoretical frameworks and models. In particular, this enables to maintain the distinction between different layers of uncertainty, not only at the risk analysis level, but also at the decision making stage. To do this, it is necessary to operate at a more elemental level of description of alternatives.

We will build our bridge on two pillars. The first one is the triplets based framework introduced by Kaplan and Garrick (1981) to describe the output of a risk analysis. The second one is the acts based decision framework due to Savage (1954) which provides the basic language of modern decision theory. These two environments are among the most popular in the respective fields and our analysis focuses on them. Extension to more general environments can be obtained by exploiting the well studied relations between the proposed basic frameworks and their more advanced versions – see e.g., Aven (2016) and Aven and Flage (2016) for more general risk analysis frameworks and Gilboa and Marinacci (2013) for decision theoretical frameworks.

The remainder of this paper is organized as follows. In Section 2, we present general definitions that provide a broad frame for the subsequent sections. Section 3, describes the risk analysis setup, with particular reference to the Kaplan and Garrick (1981) setup. Section 4 presents the decision theoretic setup, starting with the Savage (1954) definition of acts and some recent extensions. In Section 5, the heart of the paper, we embed the former setup in the latter. Sections 6 and 7 put at work our translation by showing how the risk analyst can access the rich toolbox of decision theoretic criteria. Section 8 is devoted to conclusions and perspectives.

2. Decision analysis and decision theory: a frame

This section reviews the decision analysis process as described and studied by Howard (1966, 2007) and provides a first preview of the relations between the objects of risk analysis and those of decision theory. While it can be skipped without affecting the flow of the paper, it provides the conceptual perspective to which the following sections adhere. In fact, our work is driven by the general aim of framing risk assessment in a decision analysis perspective. This is in line with the manifesto of decision analysis put forward by Howard (1966, 2007).

According to Howard (2007), decision analysis can be imagined as a process consisting of four steps:

1. the identification of the available alternatives (also called risk management options, courses of action, acts, decisions),
2. the description of the uncertain consequences generated by these alternatives,
3. the specification of the decision maker's preferences among alternatives,
4. the computation of the best alternative among those available.

Step 1 provides a list of available alternatives (e.g., different renovation plans for a light-water reactor). It can be either the output of a risk analysis in which the risk analysts produce all conceivable alternatives (for an unknown decision maker, see Paté-Cornell, 2007), or an input from the decision maker who is aware of the available options and binding constraints.

Step 2 is the crucial output of a risk analysis. It describes the risk associated with each alternative (that is, the consequences of choosing that alternative and the corresponding uncertainties). A successful method of performing this description is due to Kaplan and Garrick (1981) and consists in identifying, for each available alternative, its failure scenarios, their likelihoods,[4] and its consequences in each scenario. This method is one of the pillars of risk assessment, adopted by many institutional decision makers such as NASA (Dezfuli et al., 2011) and the US Nuclear Regulatory Commission (NRC, 2009).

Step 3 is specific of risk management (decision making) and describes the choice rules that the decision maker is placing on himself, or that he agrees upon, in choosing among alternatives, as in Howard (2007). In this case, the decision theoretic counterpart of these rules are prescriptive axioms,[5] that is, formal statements about the decision maker's laws of behavior.

[3] The common acceptation of *aleatory uncertainty* is the physical variability present in a given system or environment. On the contrary, *epistemic uncertainty* refers to the lack of knowledge about the given system or environment. As such, for any given system or environment, the first cannot be reduced, while the latter can. Of course, although this decomposition of uncertainty is operationally convenient and its use is widespread, it can be argued that the qualitative difference between the two types of uncertainty is not always clearcut. This may undermine the legitimacy of its application in modeling, see Winkler (1996) for an insightful discussion.

[4] The term likelihood here is deliberately left undefined because different specifications give rise to the different formats considered by Kaplan and Garrick (see Section 3 for details).

[5] It could be argued that also descriptive axioms and considerations may be relevant for decision analysis purposes. See Section 7.2, for an opening in the direction of descriptive decision analysis.