Reliability Engineering and System Safety 94 (2009) 1491–1498

Contents lists available at ScienceDirect

Reliability Engineering and System Safety

journal homepage: www.elsevier.com/locate/ress

Use of decision criteria based on expected values to support decision-making in a production assurance and safety setting

T. Aven *, R. Flage

University of Stavanger, Norway

ARTICLE INFO

Available online 20 February 2009

Keywords:
Uncertainty
Risk
Decision criteria
Expected net present value
Cost–benefit analysis
Cautionary/precautionary principle

ABSTRACT

We consider decision problems related to production assurance and safety. The issue is to what extent we should use decision criteria based on expected values, such as the expected net present value (E[NPV]) and the expected cost per expected number of saved lives (ICAF), to guide the decision. Such criteria are recognised as practical tools for supporting decision-making under uncertainty, but is uncertainty adequately taken into account by these criteria? Based on the prevailing practice and the existing literature, we conclude that there is a need for a clarification of the rationale of these criteria. Adjustments of the standard approaches have been suggested to reflect risks and uncertainties, but can cautionary and precautionary concerns be replaced by formulae and mechanical procedures? These issues are discussed in the present paper, particularly addressing the company level. We argue that the search for such formulae and procedures should be replaced by a more balanced perspective acknowledging that there will always be a need for management review and judgment beyond the realm of the analyses. Most of the suggested adjustments of the E[NPV] and ICAF approaches should be avoided. They add more confusion than value.

1. Introduction

A number of decision analysis methods are available to company or project management faced with the evaluation of decision alternatives under uncertainty. The methods include expected utility analysis, cost–benefit analysis, cost-effectiveness analysis and multi-attribute analysis. As an example, according to subjective expected utility theory rational behaviour for a single decision-maker is equivalent with maximising expected utility, i.e. with choosing the decision alternative with the highest expected utility; see e.g. Lindley [1] and Clemen [2]. Its logical basis gives the expected utility theory a strong position as a normative theory, but the utility concept is difficult to implement in practical decision-making. The practical solution to this problem is often to use cost–benefit analyses based on expected net present value (E[NPV]) calculations. To calculate the net present value the relevant cash flows (the movement of money into and out of the business) are specified and the time value of money is taken into account by discounting future cash flows. When the cash flows are uncertain, which is usually the case, they are represented by their expected values, and the E[NPV] is obtained. The discount rate used to calculate the E[NPV] is adjusted to compensate for uncertainties (risk). However, not all types of uncertainties are considered relevant when determining the magnitude of the risk-adjusted discount rate, as shown by the portfolio theory; see e.g. Levy and Sarnat [3] and Varian [4]. Portfolio theory justifies the ignorance of unsystematic risk and states that only systematic risk associated with a project is relevant when taking a portfolio perspective. Systematic risk relates to general market movements, for example the risk associated with political events, whereas unsystematic risk relates to project-specific uncertainties, for example the risk related to accidents.

In practice, cost-effectiveness indices such as the expected cost per expected number of saved lives (often referred to as the implied cost of averting a statistical fatality, ICAF) are often used instead of full cost–benefit analyses. If a measure costs 2 million euros and the risk analysis shows that the measure will reduce the number of expected fatalities by 0.1, then the ICAF is equal to $2/0.1 = 20$ million euros. By comparing this number with reference values, we can assess the effectiveness of the measure.

These tools, the E[NPV] and the ICAF, have a strong position in the industry. They are frequently used to support decision-making in safety and security contexts as well as in production assurance (e.g. [5–7]), which are the areas of main concern in this paper. Theoretically there is also strong support for the use of expected value-based decision criteria. The main justification is the law of large numbers, saying that the average of a number of random quantities can be accurately approximated by the expected value when the number of quantities is high. The portfolio theory plays

* Corresponding author.
E-mail address: terje.aven@uis.no (T. Aven).

0951-8320/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ress.2009.02.007

a similar role in economic theory—it justifies the use of expected values to support decision-making when considering a large number of projects (and ignoring the systematic risk).

Nonetheless, the literature includes a number of attempts to modify these approaches to reflect risk aversion—we (i.e. the decision-makers) dislike negative consequences so much that these are given more weight than what is justified by reference to the expected value [3]. It is acknowledged that we need to take into account risks and uncertainties, and see beyond the computed expected values. However, there exist "a million ways" of extending the traditional approach based on the E[NPV] and the ICAF. How should we determine what is the correct or best modification? There needs to be a rationale supporting the approach.

But such a rationale is difficult to find. The extended approaches have a strong element of arbitrariness in the way they are defined, so care has to be shown when using these approaches.

We go one step further. In this paper we argue that most of these approaches should be avoided. The arbitrariness is one issue. Equally important is the failure to acknowledge that caution and precaution in cases of uncertainty cannot be captured by a probabilistic approach alone. Probability is not a "perfect tool" for expressing uncertainty, and decision criteria based on probabilities must take this into account. This conclusion cannot be fully appreciated without considering the fundamentals concerning the understanding of probabilities and expected values, as well as the cautionary and precautionary principles.

To structure the discussion we distinguish between three types of decision situations:

(1) Known, "objective" probability distributions can be established.
(2) More or less complete ignorance.
(3) A situation between the two extremes (1) and (2).

In practice, situation (3) normally applies, but it is useful for the discussion to consider the extreme cases (1) and (2).

The limitations of using expected values to support decision-making in face of risk and uncertainties have been stressed by many researchers, see e.g. Haimes [8], who highlights that expected value decision-making is misleading for rare and extreme events. The expected value (the mean or the central tendency) does not adequately capture events with low probabilities and high consequences [8, p. 41]. See also Abrahamsen et al. [9] and Aven and Abrahamsen [10], who point at the need for seeing beyond expected values in safety management. Risk reduction in a safety context cannot be measured and evaluated simply by computing expected values. The present paper extends the work of Abrahamsen et al. [9] and Aven and Abrahamsen [10] by providing a more in-depth analysis of the scope and boundaries for using the expected value-based approaches such as the E[NPV] and ICAF, with adjustments. We obtain new insights by considering the three different types of decision situations mentioned above, and distinguishing between uncertainty about future quantities, "objective" probability distributions, and probabilities assigned to express uncertainty given some background knowledge.

The paper is organised as follows. In Section 2 we summarise the basic ideas of the cautionary and precautionary principles in risk management. In Section 3 we review and discuss some of the adjusted E[NPV] and ICAF approaches. Section 4 then reconsiders the issues using the three types of decision problems as a starting point: How should we use the E[NPV] and ICAF approaches, with adjustments, in the decision-making process? Section 5 provides some conclusions.

Uncertainty is understood as lack of knowledge about unknown quantities, and uncertainty is seen as a main component of risk. For the purpose of this paper we do not need to provide a specific definition of risk. What is required is the acknowledgement that to describe risk we need to take into account both uncertainties and the consequences (or the severity of the consequences) of the activity considered, i.e. risk comprises the two dimensions:

- Consequences or outcomes. We are concerned about consequences or outcomes that affect what humans value, and in particular undesirable outcomes. We often distinguish between initiating events (undesirable events) and their consequences. For example: the occurrence of a terrorist attack and the associated consequences.
- Uncertainties, and probabilities specifying the likelihood of each outcome or sets of outcomes.

Some examples of definitions of risk consistent with this perspective are:

1. Risk refers to uncertainty of outcome, of actions and events [11].
2. Risk is equal to the combination of possible events/consequences and associated uncertainties [12].
3. Risk is uncertainty about and severity of the consequences (or outcomes) of an event or human action with respect to something that humans value [13].

When speaking about risk and uncertainty in the following we think about uncertainties and likelihood seen in relation to the initiating events and consequences (outcomes).

2. Review of the cautionary and precautionary principles

The cautionary principle is a basic principle in risk management, expressing that in the face of uncertainty, caution should be a ruling principle, for example by not starting an activity or by implementing measures to reduce risks and uncertainties [5,14]. The level of caution adopted will of course have to be balanced against other concerns, such as costs. However, all industries would introduce some minimum requirements to protect people and the environment, and these requirements can be considered justified by reference to the cautionary principle.

For example, in the Norwegian petroleum industry it is a regulatory requirement that the living quarters on an installation should be protected by fireproof panels of a certain quality, for walls facing process and drilling areas [15, Section 30a]. This is a standard adopted to obtain a minimum safety level. It is based on established practice of many years of operation of process plants. A fire may occur, representing a hazard for the personnel, and in the case of such an event the personnel in the living quarters should be protected. The assigned probability for the living quarter on a specific installation being exposed to fire may be judged as low, but we know that fires occur from time to time in such plants. It does not matter whether we calculate a probability of x or y, as long as we consider the risk to be significant; and this type of risk has been judged significant by the authorities. The justification is experience from similar plants as well as sound judgments. A fire may occur—it is not an unlikely event, and we should therefore be prepared. We need no references to