# Some Dimensions of Risk not Often Considered by Engineers

Felix Redmill
Redmill Consultancy
Email: Felix.Redmill@ncl.ac.uk

## 1 Introduction

There is a continuing debate on the competence of lay people to make decisions involving risk. Some, mainly in the engineering and scientific camps, hold that risk decisions are a matter only for experts. They maintain that the perception of risk by the public at large is misguided, and that if the public were appropriately educated they would recognise their own error and the correctness of the risk analysts.

Others, mostly in the social sciences camp, contend that despite the discrepancy between the public's perceptions of risk and the results of risk analysts, the public is not irrational. They argue that risk is not objectively measurable, risk analysis is not a wholly objective process, and the public's perception is as valid as that of experts and should be taken into account. Indeed, every member of the public makes risk decisions continually throughout life.

Both views are in some measure correct, depending on the circumstances. Risk analysis is not wholly objective. Indeed, estimates of risk, whether made by scientists or lay people, cannot escape subjectivity, which affects all stages of risk analysis, from the identification of hazards to the assessment of risk tolerability. But subjectivity is also crucial, for risk analysis demands judgement. Moreover, the issue should be less whether risk analysis is wholly objective than whether it is useful, and numerous safety-related but trouble-free plants, processes and products testify to its utility and its importance.

At the same time there needs to be a distinction between risk analysis and the decision-making process into which it feeds. In industries in which the risks are well understood, it is not unusual for tolerability decisions to be taken by experts. But, in general, the results of risk analysis should be only one of many inputs to decision-making. This is particularly so in fields, such as public policy, where the general public is affected and the risks are often not well understood. Indeed, current political decision-making includes numerous techniques for including (or at least hearing) public opinions.

The purpose of this paper is to explore the subject of risk and to offer a brief insight into psychological research that has revealed a great deal about lay people's perceptions of risk. It is hoped to offer engineers new perspectives and some ways of improving the process of risk analysis.

-------------------------------------------

[1] Published in Journal of System Safety, Vol. 38, No. 4, Fourth Quarter 2002
and is an edited version of an article published in the Computing & Control Engineering Journal (IEE), Vol. 13, No. 6, December 2002

## 2 A Note on the Language and Communication of Risk

In order to develop a deep understanding of a concept - or, at least, to be able to communicate its nuances with great precision - an adequate vocabulary is needed. The concept of risk is extremely broad, yet its vocabulary is limited. We rely heavily on two words, 'risk' and 'hazard', which , though defined synonymously in the dictionary, are given different meanings in risk analysis. But even experts are not consistent in their use (as can be seen in their writing). Because the two words are used to communicate many different meanings and nuances, it is inevitable that our understanding will depend as much on intuition, our own past experiences, our values and our emotions, as on what is intended.

Dependence on intuition reflects the way in which we deal with risk in our lives, throughout which we make risky decisions, mostly without conscious calculation. But intuition is liable to be misleading, particularly in cross-discipline communication. Risk information is communicated not only between experts in the same field but also across disciplines, between domain experts and politicians, between experts and the public, between politicians and the public, between lay people, and by the media to everyone. Communication occurs not only to explain or justify decisions already taken, but also to provide information on which others might base decisions. Without an adequate vocabulary with which to describe risk, a great deal of miscommunication and misunderstanding occurs.

## 3 Some Thoughts on Definition

The word 'risk' is variously used to mean 'probability' (or, more generally 'likelihood'), an unwanted consequence (outcome), and chance. It may also mean 'danger' and, as a verb, 'to expose to danger'. One dictionary definition of risk is 'to expose to risk', and the same dictionary gives another meaning as 'a person or thing causing a risk'.

Engineering definitions combine probability and consequence. The Royal Society (1992) defines risk as 'the probability that a particular adverse event occurs during a stated period of time, or results from a particular challenge'. This calls for the adverse event to be clearly defined - and, if several adverse events are possible, each will carry a different probability of occurrence and thus a different risk.

The International Electrotechnical Commission's definition is: 'Combination of the probability of occurrence of harm and the severity of that harm' (IEC 2000). This is clearly not a definition. It is imprecise and allows interpretation of how the two components of risk may be combined. Such openness to interpretation is normally contrary to the purpose of a definition, but in this case there is an advantage. It allows a quantitative combination when numeric values are feasible and a qualitative combination when they are not. Qualitative combination may take a number of possible forms, two being the risk graph and the risk matrix.

The engineering definition in terms of probability and outcome carries the implicit assumption that there is a risk 'out there' that can be measured or estimated more or less objectively. But a great deal of research in the social sciences has led to other conclusions. Studies by psychologists have shown that people do not restrict their perceptions of risk to these two attributes, but base judgements on a number of factors, including values. Indeed, wearing our 'domestic' rather than 'engineering' hat, we are likely to understand the point. Our feelings about risk, in the face of an earthquake, a terrorist attack, or war, are, typically, a mixture of facts and values, to which emotions such as fear are added. Our judgements are influenced by all these factors.

Some sociologists have claimed that risk is constructed subjectively according to social norms and conditions, and anthropologists propose that cultural, gender and other human differences account, at least in part, for different perceptions of the same risks.

Rayner (1992) puts forward the suggestion that the public is concerned not so much with a risk-free life but with trust, liability and consent - which he abbreviates to TLC. He defines risk as:
R = PM + TLC (where PM is the product of probability and magnitude). There is a conceptual chain, he says, at the engineering end of which risk = PM, and at the societal end of which risk = TLC. However, Rayner did not propose a unit of risk that could be applied consistently along the entire scale.

## 4 Risk as a Decision Process

Risk may be represented in the form of a decision tree, as in Figure 1 where a decision problem carries two options, A and B. A is the option to do nothing (maintain the status quo) and B has two possible outcomes, R with a probability of $p$ and S with a probability of $1 - p$.

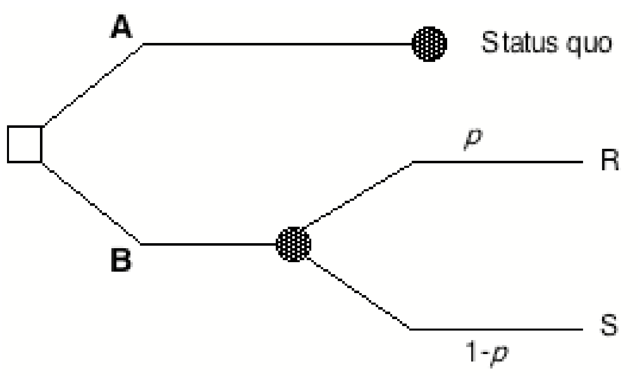


*Figure 1: Risk as Represented by a Decision Tree*

The model is applicable to any decision-making process. A gambler must decide whether to leave his money in his pocket (option A) or to place it on a bet which offers a probability $p$ of winning (outcome R) and a probability $1 - p$ of loosing (outcome S). An example in commerce is the decision of whether to continue to produce and sell a product or to replace it with an 'new improved' one.

Decision problems often carry more than two options and a number of possible outcomes that increases with the options, but they can be modelled by expanding the simple decision tree accordingly.

A decision tree is ideal for demonstrating the concept of 'expected value' - a gain or loss that is equal to the probability of a given outcome multiplied by the value of that outcome. This is seen to be equivalent to the engineering definition of risk.

Considering risk as a decision-making model is not merely of academic interest. At the point of any decision we must choose between a number of options, each carrying benefits and costs. Risk management is making, and acting on, judgements about the two.

## 5 A Risk Model

Adams (1999) identifies three categories of risk and proposes the model of Figure 2 for their representation. Risks perceived directly include riding a bicycle and driving a car. But even these are open to perception: the child riding the bicycle or the teenager driving the car may perceive a significantly smaller risk than his or her parents. Risks perceived through science, such as those posed by the organisms which cause infectious diseases, are only known because of scientific investigation. Virtual risks are those about which scientists do not or cannot agree, the implication being that though we may fear them, we are not even sure that they are risks. An example is genetically modified organisms.

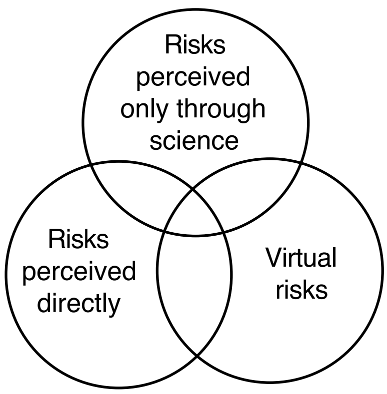


*Figure 2: Adams' model of three types of risk*

The overlap of the circles in the model indicates that the boundaries between the three types of risk are sometimes indistinct. What is now a virtual risk may, later, as the result of research, become a risk perceived through science. Then, if the research results were discredited, it could revert to being a virtual risk. So, what is perceived to be a risk, and how great the risk is perceived to be, depends, at least to some extent, on who is doing the perceiving and from what perspective. The overlaps in Adams' model represent uncertainties resulting from different perspectives of risk.

One of the reasons for the polarisation in the risk debate is that the two sides are often considering different types of risk. Engineers are in the habit of dealing with 'risks perceived directly', such as risk posed by process plant and hazardous products. Though their risk analyses may not be wholly objective, they are useful in that they lead to identification and mitigation of risks - and so it is instructive to distinguish between the usefulness of risk analysis and the subjectivity involved in it. But the social scientists are often considering the risks that pose conundrums to policy decision-makers, such as governments, and these are the 'virtual risks' in Adams' model. In them there is uncertainty - often considerable uncertainty - such that the assumptions implicit in risk analysis make the process unreliable, in which case it may reasonably be argued that the public's opinion is as valid as that of the experts.

## 6 Risk Perception

Early psychological risk research tested the assumption that humans base their decisions on rational processes - where 'rational' implied logical, consistent and in keeping with what probability theory would show to be 'expected' - i.e. 'utility theory'. This proposes that the 'expected value' of any outcome is calculated as the product of the outcome's value and its probability, and that the expected value of an option is the sum of the expected values of all its possible outcomes. Thus, if an option, A, offers two outcomes, with values R and S and probabilities $p$ and $1 - p$ respectively, the expected value of the option, EV[A], is:
$EV[A] = R(p) + S(1 - p)$

The theory carried the assumption that if a decision-maker did not maximise the expected value, it was because the differences between expected values were small and difficult to discern.

But psychological research showed that humans do not make risky decisions by mathematical-type computations. Indeed, very few are capable of probabilistic analysis of the many items of information from disparate sources that would be necessary for such computations. In addition, the expected value would not necessarily be the best option in any given situation, anyway. Expected value theory (like probability in general) is based on repeated trials and does not hold for one-off decisions, which is what ordinary humans mostly have to cope with.

One of the simplest and most basic principles of the normative utility theory, transitivity, which concerns consistency of choice, was found not to hold in human decision-making. A relationship between x, y and z is transitive if for all x, y, z:
$x \geq y$ and $y \geq z$ imply that $x \geq z$
Clearly a person making choices between x, y and z would be inconsistent and contrary to the theory if intransitive. But subjects were found to be intransitive. When faced with repeated choices between x and y, people often chose x in some circumstances and y in others. Moreover, the changes in preference did not only occur after changes in the decision-makers, such as learning. Someone who preferred y to x and z to y did not necessarily prefer z to x.

Humans use mental strategies and rules - referred to as 'heuristics' - to simplify complex decision-making. Heuristics involve mental shortcuts and approximations in order to cope with disparate information. In many cases they work well, but in others they become biases which distort risk perception and decision-making. Three important heuristics are 'availability', 'overconfidence' and 'representativeness' (see Kahneman, Slovic and Tversky (1982) for a collection of research papers).

Availability, concerns how readily information that is relevant, or thought to be relevant, to the decision in hand comes to mind. Its effect is to increase the judged likelihood of an event if the event is easy to recall or imagine. When availability is informed by experience of the frequency of events (for example, in a purely local context), it may be an accurate basis of judgement, but when it is conditioned by factors unrelated to frequency, such as a vivid news item, it can be highly misleading. The wide and dramatic reporting of a rarely occurring event can lead to an increase in its judged probability.

Overconfidence can result from a lack of awareness of the assumptions on which our judgements are based and a failure to appreciate what we don't know.

Representativeness, is a subjective judgement of the extent to which the event in question 'is similar in essential properties to its parent population', or 'reflects the salient features of the process by which it is generated'. It may introduce two kinds of systematic error into judgements. First, it may give undue influence to variables that affect representativeness but not probability, and second, it may reduce the apparent importance of variables crucial to determining probability but unrelated to representativeness. Clearly, this can affect risk judgements. For example, there is high confidence that very large samples will be highly representative of the population from which they are drawn, but it has been shown that people's intuitions about random sampling appear to assume the same of small samples. A consequence is that a scientist or risk analyst would have exaggerated confidence in the validity of conclusions based on small samples.

Heuristics apply in the brains of experts just as they do in those of lay people. For example, Henrion and Fischhoff (1986), in a study of scientific work, found significant underestimation of errors and the likelihood of errors.

A theory to account for the way in which we make choices between options, or 'prospects', and for our biases, is Prospect Theory (Kahneman and Tversky 1979). Suppose we are offered a choice between two gifts: (a) a certain $50, or (b) a 60% chance of getting $100 and a 40% chance of getting nothing. By normative theory, the expected value of (a) is 50 x 1 = $50, and that of (b) is 100 x 0.6 + 0 x 0.4 = $60. Yet it turns out that most people choose the certain gain and shun the gamble. This apparent risk aversion (at least in the face of gain) suggests that normative theory does not apply to humans.

Prospect Theory does not dismiss expected utility theory, but modifies it to accommodate the expressed preferences of humans. It expresses outcomes as positive or negative deviations (gains or losses) from a neutral reference outcome with a value of zero, and the 'value function' is roughly S-shaped, with monotonic increase and decrease, but with the slopes being convex above the reference point and concave below it (see Figure 3). Because of the convexity and concavity, the difference in subjective value for gains is greater at low values (e.g. between $10 and $20) than at high values (e.g. between $110 and $120) and the same thing holds for losses. People (in general) therefore place a higher value on reducing a risk by a given amount at low values (e.g. to eradicate it) than on reducing it by the same amount at a higher point on the value curve.

A further attribute of the subjective value function is that the descent of the losses part is steeper than the ascent of the gains part, showing that the displeasure associated with losing a given amount is greater than the pleasure at winning a corresponding sum. Prospect Theory also shows that low probabilities (except zero) are overweighted (i.e. people are over-concerned about unlikely but high-consequence events) and high probabilities (except certainty) are underweighted.

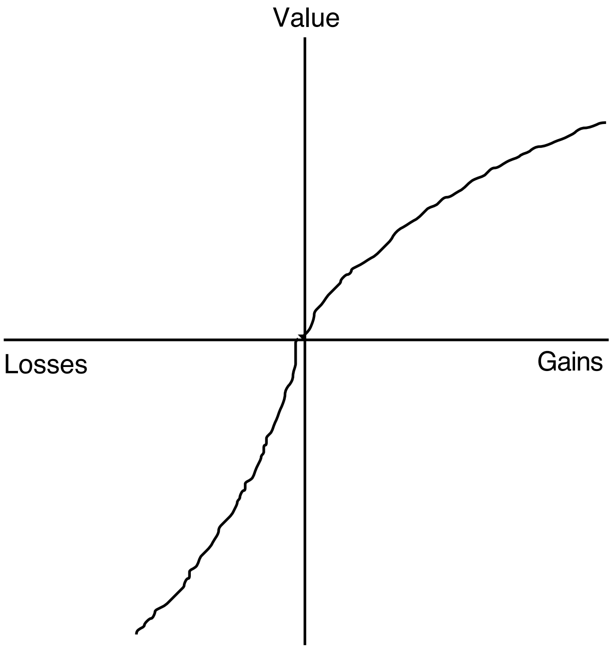


*Figure 3: The nature of a value function*

Another significant influence on decision-making is 'framing' - the way in which problem information (e.g. the available options and their outcomes) is expressed. In one experiment, Tversky and Kahneman (1981) achieved a complete preference reversal by framing the possible outcomes of the options for a public health programme first in terms of lives saved and then in terms of lives lost. The importance of framing on the communication of risk information is clear and far-reaching and is well understood by advertising experts.

Another branch of research, 'The Psychometric Paradigm', was carried out to discover the factors involved in risk perception and how lay people's perceptions differed from those of 'experts' (see Slovic 1992 for a review). Considering thirty technological risks, it was found that risk judgements by experts' in the particular field tended to be based on the expected numbers of fatalities, but lay people's risk perceptions were also based on qualitative components of the risks. This was not taken to mean that lay people are irrational, but that they use a broader definition of risk than experts when making judgements about which risks are of concern to them. But since experts are also lay people - though with specialist knowledge in given fields - they too are likely to be influenced by qualitative factors, particularly outside of their specialist areas.

It has also been found that different people attribute different characteristics to the same risk, which supports the suggestion that the qualitative risk characteristics are constructs of people rather than of the hazards. Some researchers have proposed that attitudes to risk are at least partially due to social and cultural influences. Whereas these hypotheses are open to argument, it is now beyond doubt that humans do not in general base risk decisions on the maximisation of expected value, but on a number of factors, including moral and ethical values.

## 7 Some Observations

Risk is a concept that almost all people think they understand. Yet no single definition of the word is universally accepted. Indeed, no single definition would cover all understandings of the risk concept, for it embraces a variety of linguistic definitions and philosophical and psychological ideas. Notions of risk lie on a scale ranging from wholly objective and measurable to wholly subjective and socially constructed. Even in engineering and science usage is not consistent.

Experiment has shown that humans, in the normal course of their lives, do not make risk decisions according to external rules. They do not calculate expected values and attempt to maximise them. They do not base judgements about risk and safety solely on probability and consequence, but on moral and ethical values and other factors such as trust in the risk managers and the degree of uncertainty involved. In the light of this, there is a continuing, and at times heated, expert-lay debate on how risk should be perceived and treated in decision-making.

In the minds of humans, the ways in which risk is perceived and risk tolerability addressed are not two-dimensional (probability and consequence) but multi-dimensional. Probabilities and consequences are certainly important, but so are psychological, social, and cultural factors, and this is reflected in the fact that risk research continues to be carried out in many disciplines, including psychology, sociology, and anthropology.

The methodical approach that engineers bring to risk analysis is of considerable importance, exemplified by the huge number of plants and products that function safely because their hazards have been identified in advance, the associated risks analysed and assessed, and risk-reduction measures put in place. Engineering has much to offer other disciplines, and its approach could beneficially be employed in many other fields, such as medicine, psychiatry and the probation service.

At the same time, when risks are not well understood, or when they affect public policy, decision-making requires information from many sources, of which risk analysis is only one. In such circumstances, the findings of the social scientists have a lot to tell us, particularly when controversy threatens. Indeed, not only do the social scientists' research findings contribute to decision making, but they could also add a useful dimension to the process of risk analysis and assessment. Engineering has not, in general, reached out to embrace these findings. Perhaps it is time for us to examine the possibilities.

## References

Adams J (1999). *Risky Business*. Adam Smith Institute, London

Henrion M and Fischhoff B (1986). Assessing Uncertainty in Physical Constants. *American Journal of Physics, 54, 791-798*

IEC (2000). *International Standard IEC 61508: Functional Safety of Electrical/Electronic/Programmable Electronic Systems*. International Electrotechnical Commission, Geneva

Kahneman D, Slovic P and Tversky A (1982). *Judgement Under Uncertainty: Heuristics and biases.* Cambridge University Press

Kahneman D and Tversky A (1979). Prospect Theory: An analysis of decision under risk. *Econometrica*, 47, 263-291

Raynor S (1992). Cultural Theory and Risk Analysis. In: KrimskY S and Golding D (eds.): *Social Theories of Risk*. Praeger, Westport

Royal Society (1992). *Risk: Analysis, Perception and Management*. Royal Society, London

Slovic P (1992). Perceptions of Risk: Reflections on the Psychometric Paradigm. In Krimsky S and Golding D (eds): *Social Theories of Risk*. Praeger, Westport

Tversky A and Kahneman D (1981). The Framing of Decisions and the Psychology of Choice. *Science*, 211, 453-458