UNCERTAINTIES IN RISK TOLERABILITY

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ABSTRACT

The management of risk is now recognised as central to the effective and efficient operation of industry and commerce and is widely practised. Risk Management has economic, political and human dimensions, which in all cases involve pivotal judgements relating to the acceptability or (as appropriate) tolerability of the criteria which underpin the executive decisions and actions in the risk management process. How robust are the techniques used to arrive at such judgements? And how can existing variations in tolerability criteria be explained or justified? The developing methodologies contain many uncertainties (for example, selection of failure cases from a range of possibilities; failure possibilities in each case; scale of modelling and consequence uncertainties; model validation; parameter values of the models used; uncertainties in enhancing and mitigating factors). How far do these uncertainties affect the validity of risk management decisions? And how sensitive are these decisions to aspects of uncertainty? How far do the influences affecting public perception of the type, nature and magnitude of any risks affect the nature of risk management? (for example, issues such as voluntary vs involuntary exposure; natural vs man-made risks, perceptions of personal control, familiarity, perceptions of benefit or disbenefit, the nature of the hazard, the nature of the threat, the special vulnerability of 'sensitive' groups, public perceptions of comparators, reversibility of effects, all may be felt to influence significantly the decision making process). Expression and communication of risk (particularly methods of calculating and expressing societal risk) may compound any problems.

RISK MANAGEMENT

Not surprisingly, there is no agreed definition of 'risk management' - the issues involved may be very complex - but it is possible to characterise the overall process into a coherent overall architecture, based on the principles of

- IDENTIFICATION -the recognition and location of any potential problem;
- ASSESSMENT - the bounding and dimensioning of any potential problem;
- CONTROL - the limiting of the scale of any potential problem, by prevention or avoidance;
- MITIGATION - the amelioration of the residual elements of the potential problem.

This is a strategy first applied, in the UK, to the control of major chemical hazards as a result of the recommendations of the UK Advisory Committee on Major Hazards but it is an overall approach which is universally applicable. Measures used to parameterize, or to limit, the component elements may vary between hazards and risks, between different components of the overall environment, or between different economic and cultural systems; but the underpinning logic of the approach remains as a taxonomy comprising overall environment, or between different economic and cultural systems (1). At the core of a risk management approach lies a simple question set. Essentially the core questions are:

WHAT IF? WHAT THEN? THEN WHAT? SO WHAT?

'What if?' requires a combination of technical expertise, experience, and a degree of imaginative insight. 'What then?' and 'Then what?' are essentially the techniques and practices of risk assessment. 'So what?' is the area of judgement, informed but not constrained by the earlier inputs. It is a decision process, often rigorous, which involves:-

a) dimensioning of likely risk with an understanding of the inherent uncertainties involved in the assessment process (answering the question 'How much of what kind of what risk of what to whom or what?)

b) reference to the likely benefits generated and the political and economic considerations associated with it

c) judgements as to tolerability or acceptability for groups directly or indirectly affected; and

d) sometimes, decisions as to further reductions in risk taking cost (including effort, and available technology) into account.

It is, in short, a process which is essentially economic and political, technically informed.

THE ROLE OF QUANTIFIED RISK ASSESSMENT (QRA) IN THE RISK ASSESSMENT AND THE DECISION MAKING PROCESSES

Quantitative risk assessment (QRA) continues to be at an infant stage of development, plagued by problems of recognition, precision, and credibility (2). A UK Royal Society report (3) laments the deep methodological division regarding such issues as the quantification and qualification of risks, the response of QRA to public perceptions of risk, and the setting of acceptable standards for decision making. According to Blockley (4), this division points to the "open-world" nature of risk problems, which Fischhoff (5) ascribes to differences in human interpretation and judgement, an inherent attribute of QRA applications in general.

QRA applications in most areas of risk are plagued by a number of practical concerns that compromise their usefulness in decision making. Hubert and Pages (6) and Saccomanno et al (7) cite a number of inconsistencies in the values assigned by different groups to various components of risk for similar problems. These inconsistencies, it is argued, have contributed to a general loss of credibility in QRA's ability to provide accurate readings of the threats posed. A 1989 Health and Safety Executive (HSE) report (8) argues that the views held by members of the public are often at variance with apparent evidence from QRA applications. Covello (9) has noted that the reasons for this cannot be dismissed as purely "irrational" or "subjective" thinking by the public concerning risk assessment in general, but rather it rests with the ability of QRA to "communicate risk" in an effective and consistent manner. Glickman et al (10) suggests that there is a wider concern that, notwithstanding the question of inconsistencies in the estimates, existing QRA models have failed to express risk in a manner that is responsive to the specific needs of users and decision makers. They argue that QRA should be made more practicable and not necessarily more technically involved. Before proceeding further along the path to "bigger and better models", a momentary halt in progress is advisable to take stock of our current position on the learning curve and map out future directions for QRA model development. Indeed, there may be many different types of learning curve to consider in risk assessment.

There are however, some generally accepted tenets:-

1. QRA must be more responsive to the needs of users and decision makers.
Both information requirements and output must be clearly defined and documented.
2. Uncertainty must be fully accounted for in the reporting of risk estimates. Risk and its components must be accompanied by confidence limits. The sensitivity of output to various assumptions concerning parameter values and inputs must be accounted for in the reporting of the risks.
3. Risk measures must be clearly defined. There should be no ambiguity concerning the nature of risks and their perspective, such as individual and societal, or absolute and relative risks. Risk communication guidelines need to be developed before the analysis begins.
4. Guidelines for decisions and the mitigation of risk must be incorporated into the QRA models. The process must lead to technically informed decisions. Where appropriate, QRA should present output in a form that can be readily used in a cost-benefit evaluation of alternative types of mitigation.

In this context QRA has three important roles to play:-

1. Provide acceptable and credible estimates of risks;
2. Inform public perception of the nature and importance of these risks; and interpret the technical results; and
3. Provide advice on mitigation in support of the decision-making process.

The provision of acceptable and credible risk estimates is an attempt to reduce uncertainty in risk estimation, recognising that, given the nature of QRA, uncertainty can never be fully eliminated. The questions to be addressed are: to whom should these estimates be acceptable and credible? and how is this to be achieved in QRA? A major U.S. National Research Council report (11) addressed part of this issue by noting that QRA can be "successful to the extent that it raises the level of understanding of relevant issues or actions and satisfies those involved that they are adequately informed within the limits of available knowledge".

The second role of QRA is to communicate risk effectively; that is, to report and interpret the technical results so as to bridge the information gap between the technical analyst and the decision maker or user (who may or may not be a technical person). One critical issue is whether existing QRA models suitably "inform" public perceptions on the actual threats posed by a given activity. Some commentators believe that at present QRA models have not contributed adequately to a complete understanding of the risks involved, so that well-informed decisions have not always been possible. This issue has been echoed widely in the literature. The 1983 Royal Society report on risk assessment noted (12):

If follows that the public not infrequently have different perceptions of events from those suggested by the objective statistical assessments made by scientists or *other experts (here referred to as QRA). Since policy is rightly directed towards the alleviation of public anxieties, this disparity can lead to large expenditures on safety measures that have low cost-effectiveness or, conversely, to the neglect of serious risks because the public (and by extension the decision makers) happen to be relatively indifferent towards them.*

The absence of communication among those involved in QRA development has contributed to much of the misunderstanding on QRA's role and how well existing models fulfil this role. Closely related to the issue of risk communication is the role of QRA in decision support (i.e. as a guide to evaluating alternative risk-mitigation strategies). In this regard, risks should be reported in a manner that suggests an appropriate course of action for specific problems. The role of QRA will be discussed in this paper from these three points of view; namely, risk uncertainty, communication, and decision support for mitigation.

RISK UNCERTAINTY

The nature and degree of uncertainty in QRA varies with the nature of the problem being addressed and how the relevant issues are perceived by the analyst. Uncertainty in the quantification of risk can take several forms:

1. "Measurement error" expressed in the formal scientific sense as the range within which a parameter is known to lie with a given level of confidence;
2. Uncertainty in the modelling process;
3. Uncertainty in whether or not there is indeed an effect to be incorporated in an estimate; and
4. Omissions of possible causes of risk because of incomplete analysis, non quantification of the ways in which human error can arise, and omission of other extreme external causes.

In many existing QRA models, uncertainty is handled in one of four ways:

1. *Use of the so-called "best estimate" approach for all input components of risk.* Frequently, the best estimate is obtained from sample averages extracted from the literature or from observed data;
2. *Erring on the side of safety.* Estimates are made considering the so-called worst-case scenario for each component of risk. The argument is made that even if the final risk estimate is incorrect, the assessment would not compromise safety. (Some may use a "cautious best estimate" approach, which is essentially a combination of the first two of these methods;)
3. *Sensitivity analysis to varying inputs.* If risk component values are uncertain, a range of possible input values is obtained for each component and the implications on the final risk estimates are assessed; and
4. *Comprehensive statistical analysis of risk inputs and outputs.*

There are, of course, serious limitations in several of these ways of handling risk uncertainty in the application of QRA. Rimington (13A) and Haigh (13B) argue that the use of the most likely estimate or erring on the safe side alone is simply not acceptable, given the high cost of the decisions involved. Sensitivity analysis addresses how a range of values in selected inputs can affect risk estimates, without addressing specifically the reliability of these estimates. As such, the uncertainty issue is not fully addressed in this approach. Another use of sensitivity analysis is to determine whether the changes in the value of inputs make any difference to the resultant outputs. If the output is insensitive to the selected input values, the question is: why worry about the reliability of these input values? Of the previously listed methods for dealing with uncertainty, a comprehensive statistical review of risk and its inputs appears to be the most desirable course of action to take, although the amount of information required to carry out this type of analysis may not always be adequate.

In adopting a statistical approach, Saccomanno and Bakir (14) note that two types of uncertainty need to be considered: (a) uncertainty in risk estimation and (b) uncertainty in the process. The first type of uncertainty is an "uncertainty of knowledge" concerned with the value of the inputs and their parameters. The second type treats risk as a random variable, with a range of possible values tending about the mean. As in any random variable, the values assigned to risk and its inputs can be represented by their unique probability density functions.

RISK ESTIMATION: SOME AVAILABLE TOOLS

Very considerable international effort has been deployed on the development of methodologies and models (the 'tools') for risk assessment and estimation. In the field of major chemical hazards, the common components are

- in identification: the use of a substance/threshold approach (and the importance of the search for a hazard or risk equivalence system);
- in assessment: the classical approaches to consequence and probabilistic assessment. These include Comparative methods, such as Process/system checklists, Safety Audit Review, Relative Ranking (eg Dow and Mond Indices), Preliminary Hazard Analysis;

Fundamental Methods such as Hazard and Operability Studies, 'What if?' Analysis, Failure Mode and Effect

Analysis, Failure Mode, Effect, and Criticality Analysis, Goal Oriented Failure Analysis; and

Logic Diagram Methods, Fault Tree Analysis, Event Tree Analysis, Cause Consequence Analysis, Human Reliability Analysis, System Success Trees.

- in control: the application and enforcement of technical, operational and legal standards; information and descriptive packages (eg the 'safety report' approach); descriptive and analytical system justifications (the 'safety case' approach); licensing approvals or other ways of granting permission.

- in mitigation: on site emergency planning; off site emergency planning; information to those who may be affected by the risks; controls over incompatible land use; siting controls for risk sources. It is an approach which (in for example the context of major chemical risks)

(a) identifies the nature and scale of use of dangerous substances;

(b) places the use in its geographical and social context;

(c) identified the type, consequence and relative likelihood of potential harm;

(d) identifies the control regime and systems (both hardware and peopleware) to obviate that potential for harm;

(e) justifies the adequacy of the level of control (in the context of any tolerability criteria) (15) and demonstrates the broadly acceptable levels of any residual risk (again in the context of tolerability criteria).

Again however, there are many uncertainties in all aspects of the above, which bear directly on risk management decisions. These, even at the basic level, include (16)

the selection of failure cases from the range of possibilities
failure probabilities for each failure case
scale of release rates and duration
conversion of a failure case to a source term for use in further calculation
the validity of the dispersion model
    meteorological inputs
    topographical inputs
    human and environmental response to toxic, pressure or thermal burdens
    ameliorating factors
    ignition factors
    and in particular
    parameter values in many of the mathematical models.

Of course, there are techniques to compensate for such uncertainties. Much effort is being expended on 'fuzzy logic' approaches; sensitivity testing, always an essential tool, is very useful here. But the criticality of such approaches demonstrates the vulnerability and impression of the models used, and the further sensitivities of risk management decisions taken on the basis of QRA outputs.

THE ROLE OF RISK MEASUREMENT IN THE COMMUNICATION OF RISK

A major role of (Q)RA is the effective communication of the risks involved. Covello (12 Ref ante) identified 19 characteristics of risk which must be considered in QRA applications if there is to be sufficient information for evaluating these risks and making appropriate decisions. These characteristics can be grouped under three major headings

- perspective on risk, which refers to ways in which risks are viewed by users and decision makers within the context of the problem being addressed
- Criteria for measuring risk, which refers to analytical output from QRA
- relevance to decision making, which addresses the broader issue of the ability of QRA to advise on an appropriate course of action.

Most QRA models express individual risk as the probability of a stated detriment (often death) per unit interval of time, often in terms of equal probability isopleths, etc. Societal risks are, however, more complex, being normally expressed either as an expectation of harm (often death) or as a plot of the frequency of N or more deaths per unit time versus the number of deaths. This latter more complete representation of societal risk is the cumulative F-N curve. Societal risk expectation is simply the expected value of the F-N curve.

There appears to be some consensus that FN curves, despite their complexities, uncertainties, and difficulties, currently offer the best means of expressing societal risk. However, various commentators have suggested ways in which the curves can be better represented. These include

a) the use of probability density functions and probability of exceedance curves (Bernouilli, exponential, and inverse quadratic), in which Vrijling et al (17) merge two specific Dutch approaches into a simple theory of acceptability,

b) extending the range of consequences reflected in the F-N relationship, to include other consequence measures - especially as these may affect different mitigating responses. The measures could include personal injury, property damage, environmental impact, and relate to both short term and long term harm.

c) using alternative ways of defining risk consequences. Here the probability of incurring fatality in the F-N curve requires an additional step in the analysis to translate 'exposure to dose' to 'fatality response', normally using a probit dose-response formulation, in which the input dose (expressed as a function of concentration and exposure time) becomes an input to a probit expression, with the dependent variable being a measure of the probability of death.

d) linking F-N curves to mitigation. This can include mitigation measures at both the individual level and at the level of official or other response

e) including monetary factors. In real terms, decisions are rarely made in the absence of financial considerations (ie. the cost of mitigation vs the benefits of risk reduction). This approach requires the risk output to be reported in such a way as to permit a thorough cost effective valuation of alternative forms of mitigation. It could involve assigning values to deaths, injuries and property values in the F-N curves and assessing the costs of alternative types of mitigation, including emergency response (inc. evacuation), containment, and clean-up, as well as risk avoidance. Some current research work by Keller & Cassidy (18) is providing useful insights into the potential of this approach, converting accident and other data to logarithmic magnitudes and analysing using Maximum Likelihood, with exponential Weibull, and a specialised Weibull, probability distribution analysis.

f) expressing uncertainty in the F-N relationship. Because uncertainty in risk estimation varies with the number of reported cases used in validating the model estimates, the uncertainty associated (for example) with very low frequency/high consequence events is likely to be greater than the uncertainties in the reverse case. Accordingly, certain regions of the F-N curve are more prone to uncertainty than other regions, and this should be taken into account in representing the results. The normal procedure for this is to establish confidence limits about each point on the F-N curve. Of course, imperfect information will always produce risk estimates that are subject to error. True values of risk are unlikely ever to be known. Confidence bands in F-N curves are helpful to decision makers because they provide a range of values within which the true value of risk lies, with a percentage level of confidence. The bands can also serve as a basis for comparing uncertain estimates from different sources.

g) use of expectation values. Frequently, societal risks in F-N curves are combined over all consequent damages and expressed as a single damage value (eg expected fatalities per year). On occasion, such use of expected values has created problems for validation of QRA models and has fostered a belief that these models are unnecessarily alarmist when compared to historical experience. This leads to a need for caution in using and interpreting QRA results based exclusively on the expected value of harm, especially when historical data may have been collected over an inappropriate time period, or the work is subject to a significant latency period.

Other quantified approaches are currently being developed for addressing aspects of societal risk. These include

(i) the use of expected (dis)utility criteria (19), which offer some advantages (but with concomitant disadvantages) over F-N curves

(ii) a Risk Index and Scaled Risk Integral approach (20). This approach is very useful in specific local cases, but is limited or not applicable in wider application.

ACCEPTABILITY AND TOLERABILITY OF RISK - DIFFERENT REGULATORY APPROACHES

In attempting to decide upon criteria which regulators can use to judge whether the risk should be incurred (taking account of any benefits) or the amount of resources which might justifiably be deployed, different types of criteria have been deployed. These include:-

utility based criteria, aiming to maximise net benefits, where cost benefit analysis (CBA) is used to calculate the difference in monetary terms between the advantages or otherwise of a particular course of action;

equity based criteria, where the premise of equal rights has led to focussing on protection of the vulnerable; and

technology based criteria, where the level of available control technology is the major determinant in choices as to risk control.

CBA has a part to play in all these approaches; but it is pivotal only to the utility approach. On some occasions multi attribute analysis may have considerable value in decision making where there are significant effects which cannot be expressed in a common (eg monetary) measure.

ABSOLUTE AND RELATIVE RISKS

Another question of importance in communicating risk is whether QRA should express risk in relative or absolute terms. The presence of uncertainty in risk estimation has fostered the belief that absolute risks are simply 'abstractions posing as truth' (21), and that given the uncertainties, only relative risks have any practical value in QRA applications. It may be that what is of interest to the decision maker (whoever this may be) is not the true value of risk, but rather insight gained on the risk involved, whether one activity is safer than another, and the degree to which this might be the case. Because only relative risks are required to answer these questions, uncertainty in obtaining absolute risks would not be relevant.

Notwithstanding difficulties in obtaining reliable estimates of absolute risk, however, the importance of these measures in certain decision situations should not be underrated. Absolute risks are most relevant in setting priorities on the cost-effectiveness of mitigation and in comparing risks to established tolerance criteria. Relative risks are most relevant when one mitigation option is compared with another and the decision maker is interested in some preferred option without a firm statement as to its costs and benefits or its acceptability vis-a-vis public risk tolerance levels, then only risks expressed in absolute terms would be relevant in decision making.

GENERAL PRINCIPLES OF RISK CRITERIA

Whatever the assessed level of risk, the decision maker is ultimately faced with the 'So What?' question, where increasingly quantitative probabilistic criteria are being applied by regulators or enforcers. Where such target criteria are applied (often in a 3-Zone situation, the middle zone embracing the 'ALARA' or 'ALARP' principle) a standard framework is emerging. This framework reflects well established approaches in international risk control, particularly related to advanced, high technology activities, such as those of the nuclear industry, the latter being expressed in the 1977 Report of the International Commission on Radiological Protection. These ICRP recommendations embody the interrelated principles of justification of practice, optimisation of radiation protection, and individual dose limits. No practice or activity involving exposure to radiation was to be adopted unless its introduction produced a positive net benefit in a society, this benefit to be maximised by the 'as low as reasonably achievable (ALARA)' principle, and inequitable distribution at the level of the individual avoided by dose limits for that individual.

Such principles apply, of course, to the control of most risks. In an ideal world, any hazardous activity would not impose risks which were disproportionate to the benefits (such benefits can form a wide spectrum, and inevitably involve economic as well as other, often less tangible, social value parameters), and any such risks would be equitably distributed amongst society in proportion to the benefits received. In practice, of course, such distribution is not possible, and the principles of distribution described above are applied in a much more general way, involving tests to ensure:-

a) whether a given risk is so great, or the outcome so unacceptable that it must be refused altogether; or

b) whether the risk is or has been made so small that no further precaution is necessary; or

c) if a risk falls between these two states, that it has been reduced to the lowest level practicable, bearing in mind the benefits flowing from its acceptance, and taking into account the costs of any further reduction.

These principles combine with other generally accepted tenets:-

d) that risks should never be imposed unnecessarily; and

e) that no individual or community should bear an unfair proportion of any risk.

Such value judgements involve very complex social processes. Hazards and risks are viewed quite differently, depending on the origins of the hazards and the nature of the risks they present. Natural hazards seem to be 'accepted' more readily than those which are man made; and hazards which presage catastrophe appear less 'acceptable' than those presenting a lower level, continuous risk. A relatively well established hierarchy of 'tolerability' has emerged, which involves issues such as:- voluntary vs involuntary exposure, 'natural' vs man-made risks, perceptions of personal control, familiarity, perceptions of benefit or disbenefit, the nature of the hazard or consequence, the nature of the threat, the special vulnerability of 'sensitive' groups, public perception of the extent and type of risk, perceptions of comparators, and the reversibility of effects.

It is a decision hierarchy which turns on the confidence of those exposed to the risks in those authorities and bodies who create and control the risks - government, the regulatory authorities, plant operators, 'experts', and the emergency services. Priority questions include:-

- does the public believe that all views and interests have been considered in the decision making process, or has there been some 'dealing?'
- does the public have the confidence in the effectiveness and independence of the regulatory authorities?
- is there a consistent and credible consensus of scientific opinion about the project that the public can trust, or do the 'experts' disagree amongst themselves?
- what is known about the quality of the project and plant management?
- are the emergency and medical services able to cope with any event, in the short or long term?

It is, in effect, a combination of physical and social detriments, in which some major elements may not be quantifiable in any meaningful way.

CONCLUSIONS

QRA is unlikely ever, of itself, to be capable to mechanistic determination of the tolerability of risk. At present, those methodologies which do exist are subject to uncertainties (which indeed may be greater than the limits of decision making); whilst major elements of the tolerability equation possess no realistic methods, quantified or otherwise, of a sophistication sufficient to produce an integrated or holistic approach. Currently, at best, QRA may allow essentially political decisions to be technically informed.

However, there is some movement towards a more consistent approach for the methodology of quantified risk assessment and analysis, and to its application. Development of criteria will necessarily accompany such progress, and may eventually lead to consistency in the 'tolerability' arena, and in the application of those criteria. Until then, the diversity, complexity and uncertainty involved in the criteria and their use will remain an obstacle to structured risk management, given the pivotal role of criteria therein, and given the sensitivity of decision making to the criteria.

The views in this paper are those of the author, and not necessarily those of HSE.

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