Quantitative Risk

RICHARD JARRETT AND MARK WESTCOTT

Introduction

A key question in policing serious crime is the allocation of resources, by which we mean not just the quantity but also the type or quality of the resource. This implies a need to generate options and to develop decision-making processes that lead to action. In the book arising from a recent symposium on Uncertainty and Risk, it was noted that there was 'an interesting tension between researchers and consultants—researchers focus on the gaps in what is known ... and consultants are oriented to synthesis in order to develop ... an approach to the issue at hand' (Bammer et al. 2008, p.290). By this definition, we are in the consultants' camp, since we are concerned to provide the means by which to make the best decisions possible, albeit in the face of uncertainty.

We have been involved in a number of risk assessment and risk management processes which ultimately lead to the allocation of resources. Much of the risk assessment is undertaken, as it should be, by groups that include staff, outside experts and stakeholders. We provide the mathematical framework that draws the material together, leading to decision-making processes that are valued and trusted by those involved. Many issues raised in that recent symposium occur in practice—disagreements over standards, definitions, the relative importance of different types of hazard—but the need to get a resolution that works is a powerful force in driving this process to a conclusion. The early sections of this chapter look at some of the important and interesting issues related to risk.

Much has been written about potential flaws in the risk assessment process (e.g. Cox 2008a). One of these is the qualitative nature of some methodologies, where terms like 'critical', 'possible' and 'occasional' are used without clear definitions appropriate to the context. This can lead to ambiguity and undesirable subjectivity. It inhibits fruitful discussion and decisive action. A quantitative approach to risk assessment reduces such problems, and brings the remaining problems into sharper focus. We illustrate this proposition by looking in more detail at a particular risk assessment tool, the Risk Matrix, which ranks and compares risks but is often used qualitatively. Our proposal, presented in more detail in Jarrett and Lin (submitted), is to determine meaningful quantitative values for consequence and likelihood, the two components of risk in our

interpretation. Specifically, we propose that consequence and likelihood scores be determined respectively as logarithms of objective measures of consequence (in terms of cost or surrogates of cost) and rate of occurrence. These numerical scores can be added to provide a risk score, which can be mapped to an expected cost. This is described in more detail in the second half of the chapter.

Such a formalism provides a broad overarching structure for risk assessment which aims to be practically useful, as objective as possible and to avoid logical inconsistencies. It does not pretend that hazards have consequences and likelihoods that can be accurately determined. Rather, it provides a risk ranking method which is unambiguously defined, and accepts that individual hazards placed within it will have levels of uncertainty associated with their exact position, due either to lack of data or to varied opinions among experts.

What is risk?

Over 2,000 years ago, the Roman statesman and philosopher Cicero wrote that the safety of the people is the supreme law (Rudd 1998, p.152). But 'complete freedom from risk is an unattainable goal, and safety [is] related to the level of risk that society regards as reasonable ... in the context of, and in comparison with, other risks in everyday life' (Department of Health 1998, Section 2.6). For this reason, Kempton (1998) says 'decision makers, be they government or members of the public, need to be better educated in interpreting estimates of risk'.

The Royal Society (1992, Section 1.3.2) defines risk as 'the chance, in quantitative terms, of a defined hazard occurring. It therefore combines a probabilistic measure of ... occurrence ... with a measure of the consequences'. Hazard is 'a situation ... that has the potential for human injury, damage to property, damage to the environment, or economic loss'. Note the distinction made between risk and hazard, terms sometimes used interchangeably in discussion.

Risk, then, has two components: a probability of occurrence and a consequence. How these are combined depends on the context, but in many cases a product of them is appropriate. This multiplication implies that the values of the components must be like physical measurements; they cannot be ranks, for example. Hence 'quantitative' occurs in the definition of risk above, and in the title of our paper.

Social scientists, among others, often need a different definition of risk. Their views are succinctly summarised in Section 1.3.4 of Royal Society (1992). Issues include subjective and socially conditioned perceptions of risk. These are particularly relevant when considering risk management.

The term likelihood is often used instead of probability, though strictly they are not synonymous. In this paper we shall use rate of occurrence, rather than probability, as the surrogate for likelihood. This leads to a specific quantitative interpretation of our risk values.

In the following sections we expand on some of these ideas.

Components of a risk analysis

When considering or analysing risk some of the matters that need to be considered are:

- the hazardous event whose occurrence would cause the risk
- the consequence (harm) associated with that event
- the population at risk
- the risk per unit of exposure
- the level of exposure of members of the population.

Exposure is a factor that can be easily overlooked. Members of a population can have very different levels of exposure to a hazard. For example, distance from a chemical facility will affect significantly a person's risk from a toxic release from the facility (the prevailing wind direction might also be relevant).

Changing any of the components changes the risk. Not considering them all can lead to erroneous conclusions. For example, raw accident statistics are not a direct measure of safety (Kempton 1998); exposure must also be considered. Hilton (1993) notes that the reduction in cycling casualties in Australia of about 25% following the introduction of compulsory wearing of helmets can be explained almost totally by a commensurate reduction in distance cycled.

A more detailed description of how to carry out a Risk Analysis can be found in *The Australian and New Zealand Standard on Risk Management* (Standards Australia 2004a), first developed in 1995, and the accompanying Handbook (Standards Australia 2004b). The need and background for such a standard are described by Cross (1995), together with a summary of the risk management process.

Scales of measurement

The nature of the measurements available for a risk analysis has important consequences. The theory originated with Stevens (1946); a good summary,

including the mathematical basis, can be found in Ford (1993). There are essentially five scales of measurement, exemplified informally below by possible 'measurements' on fruit.

- *nominal* (is the fruit an apple or an orange?)
- *ordinal* (grade apples by size)
- *interval* (what weight class does an apple belong to?)
- *ratio* (what weight is an apple?)
- *absolute* (how many apples?)

To do arithmetic on data, the measurements must be on an interval scale, at least. Ranks, the best-known example of ordinal data, cannot be sensibly added, for instance. The standard Risk Matrix, to be introduced shortly, uses ordinal scales for both consequence and likelihood and this creates problems with combining them to form a measure of risk.

Quantitative risk analysis typically uses data on one of the last three scales. However, a lot of policy and social discussion involves data on a nominal or ordinal scale. This can cause difficulties when interpretation or comparison is required.

Hodge and Walpole (1999), using systems in defence as their example, discuss types of data by considering levels of complexity as shown in Figure 1, taken from their paper. The connection with our discussion is that detailed quantitative analysis usually occurs towards the left-hand end of the curve, where agreement and certainty are high. However, the results of such an analysis are then often used and discussed at the right-hand, or 'social' end of the graph, where agreement and certainty can be much less clear.

Perception of risk

Even if there is a reliable calculation of risk, based on sound data or an agreed model, this can legitimately be perceived in very different ways. Perception is a subjective and personal matter. Here are some examples.

1. If a medical procedure has a relatively high risk and an individual perceives it as non-essential, they are unlikely to undergo the procedure. If, however, the alternative is death within a very short time, the risk might be considered acceptable.
2. The risk associated with climbing high mountains would be considered unacceptably great by most individuals, including the authors. However, Andrew Lock, the first Australian to climb all 14 mountains over 8000m

(see <http://www.andrew-lock.com>), presumably regards this risk as quite acceptable.

3. There is a tendency to regard a hazard as more serious if it kills a large number of people should it occur, even if the overall death rate from the hazard is no greater than that from another hazard which occurs more frequently but kills far fewer people per occurrence. In Australia, the 2008 national road toll from road accidents was 1,464 (Department of Infrastructure, Transport, Regional Development and Local Government 2009). As far as we know, there is no evidence that Australians have decreased their road travel because of this figure, so presumably the risk is considered acceptable by most. If, however, this number of people died in 2 or 3 major air incidents in one year, it is almost certain there would be major public outcry, the use of air transport would (at least temporarily) decrease, and major changes to air transport policy and operations would occur.
4. This is discussed in the literature as 'societal risk' (Vrijling & van Gelder 1997) and typically gives greater weight to more severe consequences in the consequence-probability combination used to calculate risk. There is a specific example in the section 'Discussion of Quantified Risk Matrices' below. A recent paper, with further references, is Horn et al. (2008).

Figure 1: General hierarchy of systems (from Hodge & Walpole 1999)

Quantification of risk

Our view is that risk assessment should aim to provide quantitative estimates, even if there is uncertainty in those estimates. The primary motivation for this is an issue of ‘measuring instruments’ that, in this case, need to provide a clear and unambiguous yardstick against which consequence and likelihood can be assessed. Van Duijne et al. (2008) note that ‘scale values such as “unlikely” and “improbable” can be interpreted as almost similar, yet risk assessors are forced to choose one of these options if both values appear on the same scale’. Without precise definitions for consequence and likelihood, the uncertainty contains two components of variation—one related to people’s different interpretations of the measuring instrument and a second related to their uncertainty in where to place a particular hazard on the scale. The aim is to remove the first of these, by using clear and unambiguous definitions.

A typical Risk Matrix, shown in Table 1, has rows as levels of consequence and columns giving levels of likelihood. Identified hazards are placed within the Risk Matrix by choosing the appropriate row and column. Standards Australia (2004a, 2004b) provide a broad methodology and specific examples. Anderson (2006) claims to have identified more than 800 versions of Risk Matrices through a search on Google. The levels in the two margins are clearly ordered, or ranked. Without further explanation they are no more than that; in particular, there is no notion of relative magnitude, so their measurement scale is ordinal. Their combination into a measure of risk is qualitative and subjective; for example, should the combinations {critical, improbable} and {negligible, occasional} be regarded as comparable risks, as they are in Table 1?

Table 1: A general Risk Matrix

Consequences	Likelihood				
	IMPROBABLE (E)	REMOTE (D)	OCCASIONAL (C)	PROBABLE (B)	FREQUENT (A)
CATASTROPHIC (4)					VERY HIGH
CRITICAL (3)				HIGH	
MARGINAL (2)			MEDIUM		
NEGLECTIBLE (1)		LOW			

Recent criticisms of Risk Matrices (Cox 2008a) question their suitability and reliability for adequately ranking the risk of a variety of hazards. Many of these criticisms relate to the degree of arbitrariness in the definition of the scales for consequence and likelihood. Table I in Cox (2008a) gives a specific example, and further discussion can be found in Edwards et al. (2009).

The gradations of risk, or iso-risk contours, in Table 1 are roughly diagonal. This suggests their developers have a more quantitative framework in mind. If so, it should be spelled out explicitly. The Risk Matrix shown in Jarrett and Lin

(submitted) has levels for both consequence and likelihood scaled in logarithmic steps, as proposed previously by Swallom (2005), van Eijenhoven and van Ravenzwaaij (1989) and Anderson (2006), *inter alia*. Table 2 provides an example with logarithmic scales (based on powers of 10), and levels based on integer steps. For example, if cost is measured in dollars, then a consequence score of 8 corresponds to a consequence of $\$10^8 = \100M , and covers consequences that are thought most likely to fall in the range $[10^{7.5}, 10^{8.5}] = [\$30\text{M}, \$300\text{M}]$. Similarly, a likelihood score of -2 corresponds to a rate of occurrence of $10^{-2} = 0.01$ per annum (if that is the period over which likelihood is assessed) and covers rates in the range $[10^{-2.5}, 10^{-1.5}] = [0.003, 0.03]$.

Table 2: The Risk Matrix with logarithmic scores and risk levels

Overall Consequence Score	Likelihood Score				
	Rare	Unlikely	Possible	Likely	Very Likely
	-4	-3	-2	-1	0
Catastrophic 10	Medium	High	Very High	Extreme	Extreme
Major 9	Low	Medium	High	Very High	Extreme
Moderate 8	Very Low	Low	Medium	High	Very High
Minor 7	Negligible	Very Low	Low	Medium	High
Insignificant 6	Negligible	Negligible	Very Low	Low	Medium

This does not imply greater accuracy in the assessments, but aims to provide a well-defined measuring instrument against which individual hazards can be judged. This reduces the uncertainty that can arise from use of more subjective scales.

The risk score is the sum of the consequence score and the likelihood score. It has a natural interpretation as the logarithm of the Risk or Expected Cost per year associated with a particular hazard. Here,

$$\text{Risk} = \text{Expected Cost} = \text{Consequence} \times \text{Likelihood}$$

and the scores sum because multiplication becomes addition on a logarithmic scale. For example, if the likelihood were a rate of 0.1 events per year and the consequence were $\$10^8$, then, on average, for nine years out of 10 the cost would be \$0, while one year in ten the cost would be $\$10^8$. Averaged over the 10 years, the cost would be $\$10^7$ per year, which is referred to as the Expected Cost. In this case, the consequence score would be 8, the likelihood score would be -1 and the risk score would be the sum of these, namely 7.

In contrast with Table 1, which is entirely qualitative, cells in Table 2 with the same risk description have the same risk score with a well-defined interpretation. The descriptions can be changed but whichever words are used their meaning in this context is quite clear. This is the objective basis foreshadowed above.

The cutoff values used to define risk levels, as shown in Table 2, will depend on (i) the actions to be taken for each risk level, and (ii) agreement that this is the action one would take for a hazard at that risk level. Table 3 provides a typical description of action (GAO 1998) to be taken for certain risk levels, so agreement is needed on the appropriate cutoff point for each action envisaged. A preferable model, however, would be to consider mitigation strategies and their costs, and determine action on the basis of some combination of reducing the highest risks and making the biggest overall reduction in risk given the finite resources available for mitigation.

Table 3: Examples of actions associated with risk levels (from GAO 1998)

Risk Level	Action required
1	Unacceptable (reduce risk through countermeasures)
2	Undesirable (management decision required)
3	Acceptable with review by management
4	Acceptable without review

The Consequence Matrix

Consequences for particular hazards, where strictly monetary, can be assessed and estimated. However, consequences often are not expressible in purely monetary terms. In a particular government-based risk assessment in which we were involved, there were seven consequence categories, as shown in Table 4, including ‘death, injury or illness’ and ‘environmental’, along with ‘economic’. The aim is to broaden the definition of consequence and to assist in defining the potential consequences of a particular hazard. Table 4 gives descriptions for the ‘moderate’ consequence score for each of these seven consequence categories. Similar descriptions are given for each of the other consequence scores, and these can be incorporated into a matrix, in which columns represent consequence categories and rows are the consequence scores (see also Standards Australia, 2004b, Table 6.2). There are three important features of this proposed Consequence Matrix:

- An increase of 1 unit in consequence score corresponds to a tenfold increase in the ‘economic’ consequence category.
- Where impacts cannot be measured in dollars, judgment and agreement between stakeholders are needed to ensure that, as far as possible, the

descriptions corresponding to a particular consequence score are seen as representing hazards of similar 'impact'. Hence each of the descriptions for moderate consequences in Table 4 is of comparable impact.

- The score allocated for each of the consequence categories is the highest score for which one or more of the dot points would be realised, should such a hazard occur.

Under this proposal, a score of, say, 8 in any column of the Matrix can be regarded as being of similar importance.

The consequence scores for a given hazard need to be combined across categories without diminishing the effects of any high consequence scores. A score of 8 corresponds to an economic impact of the order of \$100M ($=\10^8). Since a score of 8 in another consequence category represents an event of similar impact, this might be regarded as having a similar 'cost'. So adding the category scores after taking a power of 10 corresponds to adding the implied costs, and taking the logarithm (log) of the sum turns it into a consequence score again. In formal terms, this can be expressed as:

- take 10 raised to the power of each category score
- add these numbers together to give an overall total
- take the logarithm to base 10 of this total to get the combined consequence score.

The overall consequence score will be higher than the maximum score across a row, by an amount related to how many times that maximum score occurs. For example, if the consequence scores are 4, 8, 6, 8, 7, 5, 4 in the seven categories, the overall consequence score is

$$\log_{10} (10^4 + 10^8 + 10^6 + 10^8 + 10^7 + 10^5 + 10^4) = \log_{10} (211,120,000) = 8.325$$

This is preferable to the average score of $(4+8+6+8+7+5+4)/7 = 6.00$, which reduces the impact of the scores of 8 to such an extent that the hazard would be regarded as having quite minor consequences. It is also preferable to the maximum (8), since it recognises that high severity in more than one category is 'worse' than having it in just one category. The maximum score achievable when the highest individual score is 8 is $\log_{10}(7 \times 10^8) = 8.85$, if all seven categories are scored at 8.

Table 4: Examples of descriptions for consequence categories

Category	Description for Moderate Consequence (Consequence Score = 8)
Death, injury or illness	<p>Multiple fatalities</p> <p>Mass very seriously ill or seriously ill casualties</p> <p>State and/or territory health system fully committed with local health system overwhelmed and/or</p> <p>Australian Government assistance considered, state and/or territory response required.</p>
Economic	<p>Impact of \$30–300 million.</p> <p>Impacts on business include:</p> <p>Travel to and within Australia disrupted</p> <p>Substantial disruption to industry and/or commerce</p> <p>Disruption of one or more national industry sectors with recovery likely to last one to three months.</p>
Social	<p>Significant and/or short-term challenge to Rule of Law, lasting up to 1 month</p> <p>Civil liberties, freedom of speech, association, movement, or religion denied or restricted for up to 1 month locally, and threatened at state level for up to 7 days</p> <p>Widespread disruption to, or destruction of, the state physical and communications infrastructure, and other essential services (including critical social infrastructure) for up to 7 days</p> <p>Isolated disruption to, or degradation of, the local education system up to 1 month, or specifically isolated disruption to state system up to 7 days.</p> <p>Extreme disruption to local participation in community, arts, cultural, sporting, and leisure activities for up to 1 month, or significant disruption at state level for up to 7 days.</p>
Environmental	<p>Damage to a conservation value of a marine bioregion, including species, communities or areas identified as of particular conservation significance where recovery extends from three to ten years</p> <p>Introduction of exotic marine/terrestrial pest species resulting in a localised incursion with substantial long-term environmental impacts or a widespread incursion with environmental follow on effects where recovery extends from three to ten years</p> <p>Industrial scale harvesting of, or trade in, any native species</p> <p>Exacerbation/causation of probable long-term decline in an important population of, or habitat for, a listed species</p> <p>Commercial harvesting of, trade in, or removal from the biomass of any listed species and/or</p> <p>Killing or removal from the biomass of individual representatives of a species listed as critically endangered.</p>
Symbolic	<p>Significant repairable damage to a nationally important symbol that is internationally recognised</p> <p>Significant irreparable damage to a nationally important symbol and/or</p> <p>Destruction of a locally important symbol.</p>
External	<p>Setback and damage to bilateral relations</p> <p>Frequent deliberate challenges to Australia's sovereignty by a foreign state.</p>
Reputational	<p>Major criticism and temporary damage to the government's parliamentary reputation</p> <p>Inquiry with detrimental findings and significant criticism leading to temporary damage to the government's reputation</p> <p>Moderate damage to Australia's national business reputation.</p>

The likelihood

Likelihood can also be expressed as a likelihood score that moves by 1 unit for each tenfold change. Jarrett and Lin (submitted) propose that probability be replaced by rate of occurrence, in which case the likelihood score can be extended arbitrarily in either direction. The likelihood score is related to the rate of occurrence by

$$\text{Rate of occurrence (}/\text{time period)} = 10^{\text{Likelihood Score}}$$

If likelihood is on an annual basis, then a likelihood score of 0 represents hazards that occur on average $10^0 = 1$ time per year. Since the rate may not be constant over time (or space), a time scale (or spatial scale) appropriate to the situation should be chosen.

Likelihood can often be assessed using past data, either internal to the organisation or external. It is harder to evaluate when the rate is low, especially in situations where such hazards have never happened before. Security risks, such as criminal or terrorist activity, often fall into this category and make it particularly difficult to estimate the likelihood (Cox 2008b). Dealing with likelihood in situations of intentional harm, where there are forces or individuals trying to find ways to breach systems of controls, is considered later.

Combining different hazards in different regions

Risk scores are typically determined for a range of hazards, often of different types and geographically dispersed. We might want to combine risk scores in various ways; for example, across threats within a region, for a given threat across regions, or across both threats and regions.

Suppose there are p hazards, with consequence scores C_i and likelihood scores L_i ($i=1, \dots, p$). The risk scores are then $R_i = C_i + L_i$. Combining across the hazards is done in the same way that consequence scores are combined:

- take 10 raised to the power of each risk score
- add these numbers together to give an overall total
- take the logarithm to base 10 of this total to get the combined consequence score.

This is based on the premise that adding the expected costs across hazards is sensible, giving a combined Risk Score of

$$R = \log \{ \text{Sum}(10^{R_i}) \} = \log \{ \text{Sum}(10^{C_i+L_i}) \},$$

and the Expected Cost is just the antilog of this risk score.

It is also possible to associate a consequence score and a likelihood score with the combined set of hazards. The rate of occurrence for a set of hazards is the sum of the rates of occurrence. Since the likelihood score is the log of these rates, the combined likelihood score is given by

$$L = \log \{ \text{Sum}(10^{Li}) \}.$$

The combined consequence score C for the set of hazards should satisfy the rule that $R = L + C$, from which it follows that

$$\begin{aligned} C &= \log \{ \text{Sum}(10^{Ci+Li}) \} - \log \{ \text{Sum}(10^{Li}) \} \\ &= \log [\{ \text{Sum}(10^{Ci+Li}) \} / \{ \text{Sum}(10^{Li}) \}]. \end{aligned}$$

Thus the combined consequence is a weighted average of the consequences of the individual hazards, weighted by the rates at which they occur. The combined likelihood score provides a rate of occurrence for a series of hazards which may have very different consequences. The combined consequence score does not now represent a single hazard, but is a summary statistic for a distribution of consequence scores represented by the set of hazards.

Discussion of quantified risk matrices

We previously gave our general views on why quantitative estimates of risk are important. Here we expand on them in the context of Risk Matrices:

- The proposed method ties consequence and likelihood scores to real, measurable quantities, thus promoting objectivity. Furthermore, data, either available or collected into the future, can provide estimates, validate previously determined values or, in cases of sparse data, augment expert elicitation data (i.e. data based on best estimates made by relevant experts).
- The proposed method is readily adapted to specific situations. For example, instead of number of events per annum, likelihood could equally be the number of events per 10 years (thus adding 1 to the likelihood scores proposed), or monthly (essentially subtracting one). Similarly, consequence scores could be considered as logarithms (base 10) of the cost in millions of dollars (thus subtracting 6).
- Expected Cost provides a direct calculation of risk and hence defines how the two factors in risk are combined and how the contours of equal risk should be drawn.

- Expected Cost is related to an insurance premium, without the margin to cover costs/profits.
- Where Expected Cost is calculated for both the presence and absence of proposed (and costed) mitigation activities, a true cost-benefit analysis of the value of mitigation can be undertaken.
- There are cases where Expected Cost might not be acceptable as the measure of risk. Other measures of risk can be used; for example, Value at Risk (VaR) in financial applications (see McNeil et al. 2005). In the context of societal risk (see earlier under Perception of Risk), van Eijenhoven and van Ravenzwaaij (1989) say 'to allow for the relative unwantedness of accidents with large consequences, it has been decided that a consequence n times greater must correspond to a chance n^2 smaller'. In this case, the Risk Score becomes

$$\text{Risk Score} = 2 \times (\text{Consequence Score}) + (\text{Likelihood Score}),$$

giving the consequence score a greater weight and effectively making the diagonals in Table 2 steeper. This increased weight to the consequence score is also suggested in Standards Australia (2004b, p. 49).

Policing serious criminal, including terrorist, activity

How would these methods be applied to policing serious crime or terrorist activity? Willis (2006) gave five recommendations to the Department of Homeland Security (DHS) in respect to terrorism risk modelling and assessment:

The US Government should consistently define terrorism risk in terms of metrics like expected annual consequences

DHS should seek robust risk estimators that account for uncertainty about terrorism risk and variance in citizen values

DHS should use event-based models to assess terrorism risk

Relying on event-based models does not mean relying entirely on a top-down process

The US Government should invest resources to bridge the gap between terrorism risk assessment and resource allocation policies that are cost effective.

These sentiments resonate well with our views on the matter and the comments could equally be applied to other serious criminal activity. The Handbook on Security Risk Management (Standards Australia 2006) advocates an approach that considers such risks to be composed of three aspects, namely:

- threat, which is taken to be the likelihood of attack
- vulnerability, which is taken to be the likelihood of success given that an attack is launched
- consequence, which is the damage achieved if an attack is launched and is successful.

As with the earlier definitions, Risk or Expected Cost can be expressed as the product of these three quantities. Each of these can be converted to a score, as described earlier, and these scores added to provide a risk score. Consequence and vulnerability can be assessed by the same methods described earlier in this chapter. Indeed, the additional consequence categories defined earlier have special significance in this context, since the aim of a terrorist attack is often not merely to cause economic damage or loss of life, but to seriously embarrass governments and increase international tensions.

The assessment of threat as a likelihood is more contentious. There is a strong view (e.g. Cox 2008b) that likelihood is inappropriate here since (i) terrorist attacks are purposeful and intentional, not probabilistic or random, and (ii) even if probabilistic, the uncertainties are far too great for any likelihood assessment. However, security forces do undertake assessments and report their results. In Australia, the National Counter-Terrorism Plan (National Counter-Terrorism Committee 2005) provides a list of four Alert Levels and a description of each level in terms of a terrorist attack, as shown in the first two columns of Table 5. These relate to the likely occurrence of an attack and are essentially qualitative. The last two columns of Table 5 show our suggested likelihood scores and timescales; the basis for which is discussed below. A geographic or context dimension can be added, locating the terrorist activity around a particular person or place.

Table 5: Proposed mapping of Australian counterterrorism alert levels to likelihood scores

Alert Level	Description	Proposed Likelihood Score	Indicative rate (Australia wide)
1=Extreme	Terrorist attack is imminent or has occurred	1	One per month
2=High	Terrorist attack is likely	0.5	One every 4 months
3=Medium	Terrorist attack could occur	0	One per year
4=Low	Terrorist attack is not expected	-0.5	One in three years

Our view is that these Alert Levels can be converted to likelihoods with sufficient accuracy to be useful. For example, the 'Extreme' alert level says an 'attack is imminent or has occurred'. In other documents the wording used is 'expected within the next two weeks'. This defines a time scale and hence can be converted to a rate of occurrence. Suppose we interpret this as 'there is a probability of 50% of an attack in the next two weeks'. Generally, this would apply only over a relatively short period, but if it were maintained for a whole year, then this probability of 50% every two weeks leads to an expected number of 13 events per year, corresponding to a likelihood score of 1.1. Given the uncertainties associated with this, we propose a likelihood score of 1 for Threat Level = 1.

If a one-step change in Alert Level represented a tenfold change in likelihood of attack, the likelihoods decrease too quickly, so Alert Level = 3 (Medium: an attack 'could occur') would give a likelihood score of -1 (once in 10 years) which seems too low. Instead, Table 5 shows a mapping of Alert Level to likelihood score where a one unit step in Alert Level corresponds to a 0.5 unit step in the score for likelihood of attack. This gives a more sensible match.

Risk is now considered as the product of two likelihoods (the second of which is conditional on the first occurring) and one consequence. In terms of our scores, we simply add the two likelihood scores and the consequence score, and the resulting risk score has the usual interpretation (the score for vulnerability is 0 when the probability of success is 1, -1 when the probability of success is 0.1, and so on). From a policing point of view, the accumulation of hazards by region could be used to determine resourcing across regions, through a reduction in any of the three terms involved in the risk calculation. Similarly, the accumulation of a hazard type across regions gives a more global view of the relative risks associated with each hazard type.

There may be complex interrelationships between different hazards in different regions. While this does not have a direct impact on the overall risk, it can have a major impact on the potential variability around that estimated risk. This highlights the need for modelling, something which is rather easier to do for crime, where there are more data available, than for terrorist activity. As an example, consider the issue of protecting critical infrastructure against terrorism using risk analysis. Haines and Longstaff (2002) note that there is increasing interdependence between interconnected infrastructures and that a terrorist attack on one can have adverse impacts on others. In Australia, an analysis of such interdependency has been done through the CIPMA project (CSIRO 2007), which involved Geoscience Australia and CSIRO, together with significant funding and input from government and the major operators of infrastructure assets. The modelling concentrated on vulnerability and consequence, in

relation to a series of defined scenarios. While extremely valuable, it was not a full risk assessment exercise, since (following our definitions) it did not include the threat; that is, the likelihood of attack.

The threat aspect is likely to be very dynamic and responsive. That is to say, if resources are committed to reducing vulnerability or consequence in a particular region, then it is likely that the activity (in our terms, the threat) will move elsewhere. It may not be reduced overall, but the target for that activity may shift, either to another region, or indeed to another type of activity. The notion of the 'attractiveness' of targets is a topic on which we are undertaking further work at present.

Conclusions

Any risk assessment that defines a risk level based on consequence and likelihood has an implied mathematical relationship. By providing a risk matrix with explicit categories, that relationship becomes evident and objective. The uncertainty that remains is confined to the placement of hazards into a well-defined structure and reflects variously the lack of data, the variety of views among participants, and uncertainty about the future.

Consequences cannot always be assessed purely in terms of monetary value. This paper allows other categories of consequences to be put onto the same scale and then shows how to combine consequence scores across these categories into an overall consequence score.

The assessment of consequence and likelihood here is rooted in values which, in principle, can be supported or validated by data. This has major benefits. It helps to create more objectivity, even when expert elicitation is used, by tying the assessments to real numerical values. Data, whether available now or collected in the future, can be used to provide estimates, validation for previously determined values or, in cases of sparse data, to augment expert elicitation data. Further, the risk levels obtained are interpretable; for example, in insurance terms.

The methodology, since it is described in terms of consequences and likelihoods, might be thought to apply strictly to those situations where hazards arise through accidents or natural causes. However, the methodology is extended here to situations where hazards arise through intentional acts, such as criminality, including terrorism. Concerns have been expressed about the appropriateness of the methodology for these situations, particularly in relation to the assessment of likelihood. However, the contention is that risk and risk mitigation must

increasingly be prepared to consider hazards across both purposeful and non-purposeful acts, in order to make appropriate use of finite risk mitigation resources.

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