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OPTIMIZATION OF RADIATION PROTECTION AS A SPECIAL CASE OF DECISION THEORY

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Abstract

PTIMIZATION OF RADIATION PROTECTION AS A SPECIAL CASE OF DECISION IEORY.

Differential cost–benefit optimization is presented as a special case of more general ocedures of decision theory that use probabilistically defined utility functions. These more neral procedures can also be applied in cases where radiation exposures are only potential, to ›timize the required level of safety features. It is shown that, for disruptive events of low obability and large resulting consequences, the concept of 'expectation' of consequences nnot be used in decision making, but that the use of probabilistically based utility functions ın conceptually assure a consistent approach in deciding the required level of safety. The ıper explores the use of utility functions of logarithmic form to assign weights to ›nsequences involving different losses of life.

. INTRODUCTION

The identification and in particular the quantification of stochastic effects has ad a very pronounced influence on the philosophy of radiation protection. For ıdiation protection purposes it is assumed that there is a proportional relationship etween dose and the probability of a stochastic effect within the relevant range ·f doses.

A consequence of the assumption of proportionality is that protection is not ıken to be absolute. A radiation source always implies some 'detriment' :xpectation of harmful stochastic effects in the exposed population groups).

The optimization requirement of radiation protection is that all doses should e kept 'as low as reasonably achievable' (ALARA) taking into account social and conomical considerations. This requirement consists in limiting the detriment rom a given practice or radiation source to a value such that further reductions re considered less significant than the additional efforts required to achieve such eductions.

Optimization, therefore, implies making a decision, and there is a wide range f possible techniques to decide what is 'reasonably achievable' in the control of ıdiation exposures. The use of any given technique implies, either explicitly or mplicitly, some value judgements about the several possible criteria that influence he decision.

Differential cost–benefit optimization has already become established in radiation protection [1], and alternative optimization techniques are being developed. A parallel development in radiation protection is expected to influence the optimization approach. This development is the extension of the principles of the dose limitation system to the case of 'probabilistic exposures', i.e. exposures that would result from random disruptive events.

In the case of 'probabilistic exposures', the use of the expectation values (implicit in cost–benefit optimization) would be invalid in the case of the contributions of low probability, high consequence situations [2]. Furthermore, the use of collective doses would be precluded if high doses, beyond the range of stochastic linearity, are possible.

It therefore seems interesting to examine the basic tools of decision analysis as a possible general procedure for optimization, applicable both to normal situations and to 'probabilistic exposures'.

2. OPTIMIZATION AS A CASE OF DECISION ANALYSIS

In the case of 'normal situations', the consequences of the residual exposures at a given protection level are stochastic effects. The actual number would always be uncertain (0, 1, 2, . . . n), with probabilities distributed in binomial distributions which in some cases could be approximated by a Poisson distribution. Probabilities would be a function of the distribution of the effective dose equivalents, and the mathematical expectation would be proportional to the collective dose.

In the case of exposures that would result from random disruptive events, a second order stochasticity would apply. Several events could occur with different probabilities, and each would lead to a distribution of doses and thus an uncertain number of stochastic effects, plus some non-stochastic effects if the resulting doses are high enough.

Both protection for normal cases and safety features to account for probabilistic exposures would involve decisions in a situation where the actual consequences are uncertain, but where probabilities can be assigned to the possible outcomes. A typical approach for decisions in such situations can be found in the use of 'utility' functions *probabilistically based.* Optimization would then involve minimizing (or maximizing) some aggregate of probabilities. This, a classical approach which can be found in decision analysis textbooks, is summarized in the following paragraphs, adapted to the case of radiation protection [3, 4].

Provided that the requirement on individual risk limitation is satisfied, the requirement of optimization of protection implies the examination of available protection options which would reduce the risks but would also involve social costs.

These protection options may be listed as O_i (O_1, O_2, . . . O_m), and must be analysed in connection with all the possible occurrences of random events

$_j$ (E_1, E_2, . . . E_n), namely the number of effects caused by the source, the robabilities of which may be denoted by P_j (P_1, P_2, . . . P_n). Obviously $\sum_j P_j = 1$, f the non-occurrence of effects is also listed as an event and if the occurrence of ne event precludes the others.

If a particular protection option O_i is selected, this involves a given social cost', including monetary costs, restrictions and inconveniences, in order to educe the probability of the possible events E_1 . . . E_n. If one assumes that a articular event E_j actually occurs in spite of the risk-reducing efforts implied by O_i, all uncertainty is removed from the problem and a definite consequence is issociated with the selected protective option. Since the protective option O_i not only has influenced the probability of occurrence of event E_j but also involves given social cost, the 'consequence' will depend on both O_i and E_j. The components of this consequence C_{ij} are not necessarily amenable to aggregation nto a single quantity.

However, it is conceptually possible to rank all the possible consequences as lefined above (i.e. C_{ij} for all values of i and j) in order, from the best to the worst, according to the preferences of the decision maker. The ranking must be *coherent*, n the sense that if a consequence C_1 is preferred to C_2 and C_2 is preferred to C_3, hen C_1 must also be preferred to C_3. It is conceivable that two consequences may e equally desirable (or undesirable).

In order to assign a probabilistically based utility value to each consequence of the ranking it is possible to design a conceptual random game. For this urpose two reference consequences, C_B and C_W, are postulated, such that C_B is etter than the 'best' of the consequences in the ranking, or at least is equally acceptable, and that no consequence is 'worse' than C_W. In the designed conceptual random game C_B and C_W are the only possible outcomes of the game, with probabilities U and 1 − U respectively, which can be selected at will.

This particular value of U, $U(C_{ij})$, is the utility of consequence C_{ij}. As defined utility can be used in probabilistic expressions. Under the equal preference concept, it is equivalent to the conditional probability of obtaining the best outcome C_B given both the protective option O_i and the actual occurrence of the event E_j:

$$U(C_{ij}) = P(C_B \mid O_i \text{ and } E_j) \qquad (1)$$

As the events E_j are mutually exclusive, and again under the equal preference concept, for a given protective option O_i the probability of the best outcome C_B is

$$P(C_B \mid O_i) = \sum_j U(C_{ij}) \cdot P_{ij} \qquad (2)$$

where P_{ij} is the probability of event E_j if protective option O_i has been implemented.

Optimization of protection involves the selection of a protective option O_i. The larger $P(C_B|O_i)$ and, as a necessary consequence, the smaller $P(C_W|O_i)$, the better is the protection option O_i, judged in the framework of preferences involved in the assignment of utility values. Optimization of protection should therefore be achieved with an option O_i such that

$$\sum_j U(C_{ij}) \cdot P_{ij} = \text{maximum} \tag{3}$$

There is an apparent element of arbitrariness in such an optimization procedure, because there is indetermination in selecting C_B and C_W of the preference random game. However, provided that they are 'better' and 'worse' than all actual possible consequences, it can readily be shown that the determination of the optimized protection option is independent of the values of C_B and C_W.

3. NORMAL SITUATIONS AND DISRUPTIVE EVENTS

Assigning probabilistic utilities, as well as ranking consequences, is basically the result of social valuations intrinsic in the concept of preference. It should be noted that judgements of this type are inherent in all procedures of radiation protection optimization. For example, in the cost–benefit optimization for normal situations, social valuations are involved in selecting the value of α, the monetary value assigned to the unit of collective dose.

As the collective dose in normal situations is proportional to the mathematical expectation of consequence (expected number of stochastic effects), the selection of a value of α implies the assignment of a monetary cost per statistical life, $v = \alpha/R$, where R is the risk of stochastic effects per unit effective dose equivalent. The selection of a value of α therefore implies a judgement of equal preference for consequences of either one more statistical death or one extra expenditure of a value v.

If decision analysis is applied to optimize protection for normal situations, using Eq. (3), utilities must be assigned to consequences involving at least the number of stochastic effects (0, 1, 2, . . . n) and the cost of the protection option O_i, namely X_i. The probabilities P_{ij} of the different consequences are a function of the distribution of doses resulting from protection option O_i, and are in turn binomially distributed, or in some cases Poissonian.

If the criteria selected for assigning utilities are linear with the actual number of stochastic effects in the range of interest, and if it is possible to aggregate this part of the consequence with the cost of the protection option as X_i/v, then Eq. (3) can easily be manipulated to give the objective function of cost–benefit optimization:

$$X_i + \alpha S_i = \text{min.} \tag{4}$$

provided no other preference criteria are taken to apply.

The situation is more complex in the case of optimization of safety features for potential disruptive events. In the case of a random accidental event the risk to an individual depends on the probability of the event and on the resulting dose. For radiation effects one deals, therefore, with effects of second order stochasticity. For example, the probability of dying (risk) as a result of a given potential disruptive event can be expressed as $P = P_1 P_2$, where P is the 'risk', P_1 is the probability of occurrence of the event which would result in a given dose, and P_2 is the conditional probability of death given that dose. For P_2, for radiation protection purposes, the probability of stochastic effects (namely fatal cancer and serious genetic effects) is taken to be of the order of 10^{-2} per sievert of effective dose equivalent [5]. On the other hand, the probability of non-stochastic effects, above the threshold, increases from zero to one over a usually small range of doses. For example, for mortality due to the acute radiation syndrome resulting from whole body irradiation, the probability at less than 2 gray is practically zero, while it is nearly one above 6 gray.

Actual consequences of disruptive events could include components which are very difficult to express in a single quantity (number of non-stochastic and stochastic effects, land contamination, cost of the protective option, etc.). However, ranking by preference and utility assignment can be carried out by the decision maker, ensuring consistent decisions.

Regarding only the number of lives lost, a differential decrease of utility with an increase of number can be assumed to depend on the actual number involved. In fact, accidents killing 1 or 100 people would be considered of quite different magnitudes, while accidents killing 10 001 or 10 100 people would be judged quite similar, although the absolute difference is the same in both cases.

Utility in these cases could be taken to be an increasing function of the total number of individuals not affected by the event, U(N – n), where N is the total number of individuals involved in the evaluation and n is the number killed in the event. It should be noted that the selection of 'best' and 'worst' consequences for assigning utilities would imply n = 0 and n = N respectively.

The relative perception of the magnitude of accidents, implying a judgement of logarithmic nature for the 'disutility' (1 – U), together with an assumption of constant risk aversion in assigning utilities over the entire range, leads to a utility function of the type

$$U(N - n) = \frac{1 - e^{-k(N-n)}}{1 - e^{-kN}}$$

where k is a constant. If in the optimization analysis it is assumed that the cost of protection can be aggregated to the number of deaths, as X_i/v, then n should be substituted by $n + X_i/v$.

A final remark is necessary. Optimization of protection involves decisions, and several other aggregative techniques and multi-attribute methods will probably be increasingly used in addition to cost-benefit optimization in radiation protection decisions. In all cases there are explicit or implicit assumptions and social judgements involved in the decision. The use of decision analysis techniques makes these assumptions and judgements more explicit and offers a coherent approach which can lead to consistent decisions.

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